# Influence of Vegetation on Water Fluxes at the Ground Level in a Semi-arid Cloud Forest in Oman

Dissertation
Zur Erlangung des akademischen Grades doctor rerum naturalium
(Dr.rer.nat.)

Vorgelegt dem Rat der Chemisch-Geowissenschaftlichen Fakultät der
Friedrich-Schiller-Universität Jena

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Die Dissertationsverteidigung fand am 09.Mai 2012 in Jena statt.

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## Zusammenfassung

Pflanzen beeinflussen in großem Maß die Wasserbilanz, insbesondere in ariden und semiariden Gebieten. Der wichtigste Einfluss ist dabei die Transpiration der Pflanzen, aber auch abwärts gerichtete Flüsse unterliegen starken Veränderungen, vor allem der Bestandsniederschlag, also der Teil des Wassers der die Pflanzenkronen passiert und an der Bodenoberfläche zur Infiltration bereit steht. Durch Interzeption und Umverteilung des Niederschlagswassers innerhalb des Kronenraums wird durch die Pflanzen eine heterogene Infiltrationsverteilung am Boden generiert die sich sowohl auf die Bodenwasserverteilung reflektiert, als auch Einfluss auf Grundwasserneubildung haben kann.

In Regionen mit häufigem Bodennebel spielen Prozesse im Kronenraum eine noch wichtiger Rolle für die räumlichen Verteilungsmuster des am Boden ankommenden Wassers sowie der Perkolation von Wasser durch die Wurzelzone. Dort wo das aride Klima Baumbewuchs zulässt, kann Nebelniederschlag durch die Baumkronen einen substantiellen Teil der Wasserbilanz ausmachen. Dies ist hat speziell in ariden Regionen einen großen Einfluss, weil der Nebelniederschlag dort auch eine lokale Veränderung der Ökosystemstruktur herbeiführen kann.

Im Rahmen dieser Arbeit wurde ein aufgeforstetes Baumgebiet im Bereich der semiariden Wolkenwälder des Dhofargebirges (Region Dhofar, Sultanat Oman) untersucht. Die Heterogenität des Nettoniederschlags innerhalb dieses Gebietes wurde getrennt für zwei Baumarten, Leucaenia und Pithicellobium, untersucht. Die Ergebnisse zeigten, dass der Bestandsniederschlag unter den beiden Arten signifikant verschieden war und dieser Effekt sogar gegenüber den aus anderen Untersuchungen bekannten Randeffekten überwog. Interessanterweise war die Kronentraufe unter beiden Arten ähnlich und Unterschiede zeigten sich vor allem im Stammabfluss. Hierdurch wurde Stammabfluss als ein wichtiger Fließpfad identifiziert, der Wasser sowohl effizient zum Boden kanalisiert, als auch die Wasserverfügbarkeit baumartenspezifischen Sektoren verändert. Zudem ist der Nebelniederschlag unter der Leucaenia Baumart deutlich höher als unter der Pithicellobium-Art. Die Ergebnisse stellen heraus, dass Baumart eine vergleichbare oder sogar stärkere Rolle als der oft zitierte Randeffekt im Hinblick auf die Generierung von Nettoniederschlag in Nebelwäldern spielt.

Weiterhin trägt Stammabfluss sehr viel stärker zu der Wasserverfügbarkeit des Bodens unterhalb der Baumkronen bei als Kronentraufe. Ergebnisse einer räumlich hochaufgelösten Detailstudie zu Stammabfluss und Kronentraufe zeigen, dass die räumlichen Muster von sowohl Stammabfluss als auch Kronentraufe eine zeitliche Stabilität besitzen. Allerdings tragen räumliche Extremwerte (statistisch Ausreißer) in Stammabfluss einem größeren Teil zur Gesamtwasserbilanzbei, als Ausreißer im der Kronentraufe (Abtropfpunkte) und sie treten

zudem häufig an derselben Stelle auf. In anderen Worten, Ausreißerpunkte gerade bei Stammabfluss tragen hauptsächlich zur Bildung von potentiellen Infiltrations-Hotspots bei.

Neben Untersuchungen mit hoher räumlichen Auflösung wurden auch Experimente mit hoher zeitlicher Auflösung durchgeführt. Hierbei wurde untersucht, wie sich die Verteilung von Stammabfluss und Kronentraufe innerhalb eines Ereignisses verhält. Hierdurch sollten Unterschiede im Kronenspeicher identifiziert werden. Durch die parallel stattfindenden Niederschlagsarten (sowohl Regen als auch von Nebelniederschlag) konnten klassische Ansätze (Leyton Methode) zur Abschätzung von Speicherkoeffizienten von Kronentraufe und Stammabfluss nur bedingt angewendet werden. Zeitlich hochaufgelöste Datenreihen der verschiedenen Interzeptionskomponenten hingegen können dennoch zum Prozessverständnis beitragen. Ergebnisse zeigen unter anderem, dass sich die Speicherkoeffizienten der beiden Baumarten nicht unterscheiden. Der höhere Stammabfluss in Leucaenia ist daher nur durch eine höhere Effizienz bei der Wasserextraktion aus den Niederschlagskomponenten zu erklären, dies kann sowohl aus erhöhtem Nebelniederschlag als auch windgetragenem Sprühregen stammen. Hierbei spielen höchstwahrscheinlich Rindenstruktur, Astneigung, und die Höhe von Leucaenia eine entscheidende Rolle, welche dabei helfen sowohl bei Nebel als auch bei Sprühregen eine hohe Niederschlagsausbeute zu erzielen.

Die vorgelegte Arbeit unterstreicht, dass Vegetation in semiariden Nebelwäldern einen entscheidenden Beitrag nicht nur zur Erhöhung des Bestandsniederschlage durch Nebelniederschlag sondern auch zu Heterogenität des infiltrierbaren Wassers leistet. Dabei kann die Baumart eine entscheidende Rolle spielen. Diese Heterogenität führt zu Hotspots von Wasserverfügbarkeit. Inwieweit diese zur Erhöhung der Grundwasserneubildung und Ökosystemdynamik beitragt sollte Gegenstand weiterer Forschungsarbeiten sein.

# Chapter I

## Introduction

Water resource is a critical factor for countries locate in arid and semi arid zones (Cui and Shao, 2005). In fact, these areas are suffering from scarcity of rainfall and high evaporation (UNEP, 1997). Rapid development in life sectors with increase of population creates massive pressure in this limited source in the absence of a substantial amount of water from atmosphere. The water is demand in agriculture, industrial, livestock and domestic requirements. United Nations Environment Programme (UNEP) creates an indicator to classify these environments by the so-called aridity index. The aridity index refers to the degree of dryness of the climate for a given area. The aridity index is defined as the ratio between the mean rainfall and potential evapotranspiration, both must have the same unit.

$$AI = \frac{P}{ETP} \tag{1.1}$$

Where $P$ is rainfall and $ETP$ is potential evapotranspiration. Hyper-arid zones consist of dry land and rare vegetation. The annual rainfall in these zones is low (<100 mm) with a lack of rainfall. The rainfall could absent for several years. The aridity index for Hyper-arid zones is 0.03. In addition, arid zones are characterized by high rainfall variability, with annual amounts ranging between 100 and 300 millimeters and aridity index range from 0.03 to 0.2. Furthermore, semi-arid zones have native vegetation which varies in species. The aridity index for semi-arid regions is estimated between 0.2 and 0.5 (UNEP, 1997; Arnold, 2010).

Cloud forests in semi arid are not famous, but this is the case in Oman precisely in Dhofar. The cloud forest in this region is finding for three months yearly. Beyond the sightseeing of green cover (trees) in arid and semi arid zones, cloud forests are a source of biodiversity and a fundamental factor that contributes in the water cycle (FAO, 2008). Cloud forests play an important role in the amount of precipitation received by certain areas (FAO, 2008). Canopies capture rainfall and fog droplets during rainy and fogy seasons (Dunisch et al., 2003), which assume to add a significant volume of water to ground water aquifers (Prada et al., 2009). In addition, the layer of leaves that fall around the tree, roots and branches prevents runoff and allows the water to percolate into the soil. Moreover, forests prevent soil from erosion and degradation by holding soil in place and provide the nutrients for soil. Trees, roots can enhance infiltration process through the soil by speeding up the water movement via root channels and limits evaporation from the soil (Wallace et al., 2005) and therefore, enhance ground water recharge.

Trees in Dhofar cloud forest assume to contribute in recharging the coastal ground water aquifers during monsoon (Khareef) season. Trees redistribute gross precipitation into stemflow and throughfall. Net precipitation found to be greater than gross precipitation in most rainfall events. In addition, tree species play a role in the magnitude of net precipitation (Bawain et al., submitted) and most of water reaches forest floor via stemflow. The stemflow in this semi arid cloud forest suggests channelizing the water quickly through the forest soil towards the costal aquifers.

Secondly, cloud forests are an environment-media for many species of plants and animals (UNEP-WCM, 2004). They protect and sustain the diversity of nature. Plants provide habitat to different types of organisms (UNEP-WCM, 2004). Animals and birds live in forest, birds build their nests on the branches of trees, insects and other organisms live in various parts of the plant.

As it knows plants absorb carbon dioxide ($co_2$) and release oxygen ($o_2$) through the process of photosynthesis. This makes plants and the green cover an Oxygen-Supply-Source for life on earth.

Thirdly, cloud forests play a vital role in ground water recharge. In general, trees intercept rainfall and reduce water run-off. Vegetation (trees and grass) modifies the precipitation input. Trees capture a significant amount of water during rain and cloudy conditions. The water arrives under canopies, infiltrates through unsaturated zones via diffusions points (throughfall) or sources points (stemflow). Stemflow points and dripping points from leafs and small brunches accelerate water to ground water aquifers as well as minimize the evaporation rates. The water has two scenarios, either returns back to the atmosphere via evaporation and transpiration or infiltrates through the soil toward ground water aquifers. The second scenario is more common in cloud forests due to fog occurrence, which assume to reduce the water loss form vegetation and soil. Hence, enhance ground water availability by recharging ground water aquifers.

Ground water plays an important role in water supply and the ecology of semiarid areas. Variability of rainfall in semi arid zones promotes ground water to be the vital source for different water uses. Ground water aquifers are used for drinking, agriculture, industrial and commercials purposes. The agricultural sector is the highest consumer sector of the sources (Garrido et al., 2005), as in Oman, it consumes 90% from the total water use. This increase in ground water demand will lead to dryness of ground water aquifers, because the abstractions rates exceed the recharging rates, considering the fact that the majority of ground water aquifers in semi arid regions are non-renewable water. This principle applies for Oman due to the country location.

## 1.1 Geography and location

Sultanate of Oman is located in the southeastern part of the Arabian Peninsula and covers a total land area of approximately 309,000 km$^2$ (fig.1.1). The land area is composed of varying topographic features: desert account for 82%, mountain ranges for 15 % and the coastal plain for 3 % of the landmass (U.S. Library of Congress, http://countrystudies.us/persian-gulf-states/45.htm in 29/5/2011). Dhofar region is approximately 1/3 of Oman area. The province extends from Ras ash Sharbathat at east to the west to border of Yemen. The southwestern portion of the coastal plain of Dhofar is regarded as one of the most beautiful in Arabian Peninsula. The highest peak is located at jabal (mountain) Samhan about 1,800 meters above sea level (http://members.tripod.com/~AZIEZ_010/res3.html, 25/12/2011). Mountain ranges are a natural barrier used to capture cloud during monsoon season.


**Fig.1.1.** The location of the sultanate of Oman in the Middle East. The study site (black circle)

## 1.2 The Khareef (monsoon) of Dhofar

Work done on the hydrology of Dhofar by earlier studies has revealed that the southern coastal Dhofar area of the southern region of Oman is governed by three main weather systems: (i) the Frontal System, occasionally yielding moderate rainfall during late December to April, originates from the Mediterranean or Red Sea,(ii) the Tropical Cyclones, originating over the Arabian Sea, during May - June and October - November, result in heavy to violent rain generally associated with high wind speeds, occurring on the average once every three to five years and (iii) the south-west monsoon (Khareef) occurring annually between late June and late September (Chebaane and Alesh, 1995). The Khareef is the most dependent precipitation in southern Dhofar, brings a continuous fog/drizzle for three months, transforming the Dhofar mountains into a green canopy during this period. This wet foggy conditions together with green, mist covered mountains of southern Dhofar, perhaps appear to be out of place for a desert portion of the entire gulf region. The exceptional Khareef season, creates a cloudy forest in Dhofar. In this region, the monsoon leads grass, shrubs and trees to growth. Vegetation varies progressively away from the coast plane, in which dense tree cover grows in valleys, on slope hills, and even shrubs are found in flatter areas. The Dhofar mountains have 900 plants including 60 endemic species.

The Khareef in Dhofar is the result of interaction of wind circulation over the Indian Ocean and the Arabian Sea with the low pressure area which persists in the desert (Nejd), caused by the progressive heat up of the interior of Arabia Al- Khali (Empty quarter) during April to May. The process leads to an excessive stratiform cloud, a persistent moist southwesterly wind and a coastal upwelling over Southern Dhofar (Price etal, 1988 ). This causes a cooling of the sea temperature, which in turn condenses the warm moist southwesterly winds moving over the coast towards the landmass generating foggy humid conditions with frequent light rain (drizzle). As the fog moves inland it is intercepted by the vegetation cover and any other natural/artificial barrier and is captured. The moisture thus captured constitutes a major portion of the total precipitation during this period. Average rainfall (1984-2006) amounts up to 114 mm in the coastal plains and up to 250 mm on the mountain range, fig.1.2. The seasonality holds for temperature and humidity with annual averages for temperature around 26 °C in the coastal plains and 21°C in the mountains (Ministry of transport and communications, 2006).

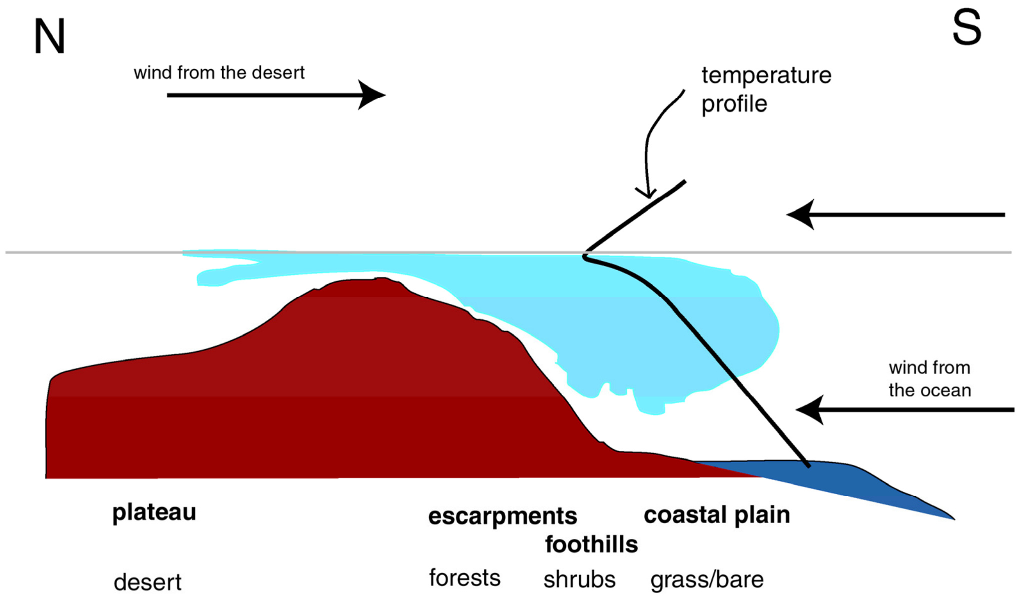


**Fig.1.2.** Schematic diagram for Khareef clouds and vegetation gradient in the Dhofar mountains (from Hildebrandt et al., 2007).

Due to the shrinking of the vegetation cover in the mountains of Dhofar as a result of over-grazing, human activities and desertification problems which extends every year. Authorities in Oman are implementing a project to re-plant trees and protect some areas from over-grazing. Re-plantation effort in Oman is start by creating enclosures. Enclosures are referred to a fenced area that is protected from animal and human destruction. The purposes of enclosures are to plant endemic or introduce trees, as well as protect some areas from grazing. These enclosures distribute over areas where cloud forest occurs. A total of twenty seven enclosures with 120 hectares in area contain total number of trees 93344 are established. Moreover, there are seven enclosures of total area of 27 hectare are used for seed-products (Collected information from ministry of agriculture, Oman). At the moment, the government of Oman is establishing more enclosures. Some of old sites are not success to survive and others are very successful project such as Tawi Attair enclosure. The site we made our study.

## 1.3 Experiment

Measurements were conducted at the Tawi Attair forest enclosure (17$^{o}$ 6' 42"N, 54$^{o}$ 31' 27"E, 650 m), a fenced property of about 5 hectares. Located on a plateau, the vegetation outside the enclosure is dominated by grass vegetation. The site is a part of several enclosures scattered over the Dhofar mountains as components of combating desertification and a biodiversity conservation project launched in 1992 used for tree re-plantation. Data for throughfall, stemflow, fog, rainfall, as well as basic climatic parameters were collected within an experiment site at the southeast corner (major wind direction, see inset Fig.1.3) of the enclosure. The experiment site occupied a total area of 7000 $m^2$. Within the experiment site, six plots were delineated and surveyed taking in account the different tree species and the different positioning towards the wind-aligned edge. Four plots of *Pithicellobium dulce* trees and two of *Leucaenia leucacephala* trees. One plot of each tree type was located at the wind-aligned edge of the enclosure fence (see Fig.1.3).

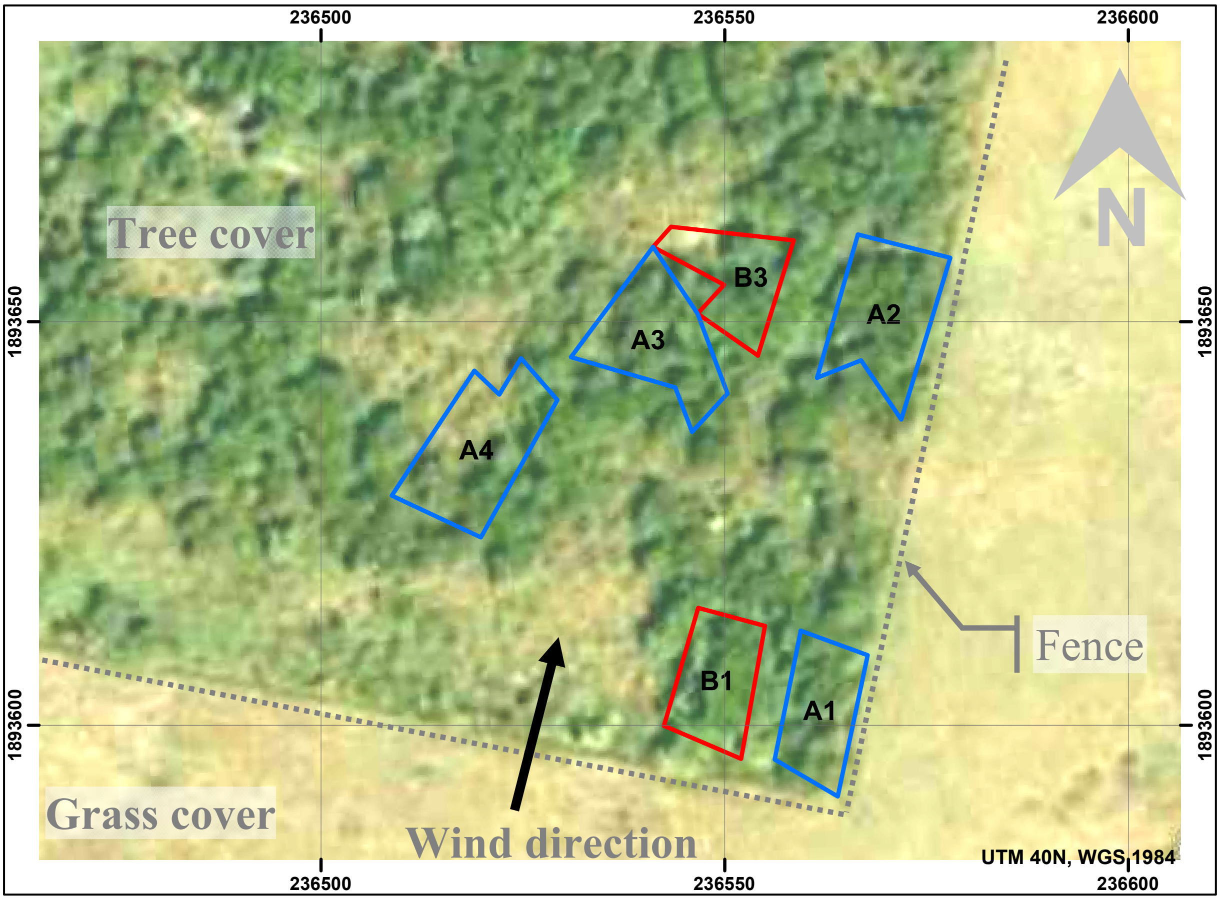


**Fig.1.3.** Schematic of experiment plots at Tawi Attair enclosure forest; (blue plots-A) *Pithicellobium dulce* trees and (red plots-B) *Leucaenia leucacephala* trees

This research proves that net precipitation within this cloud forest is more influenced by tree species than edge effect. It is found that periods of net precipitation by *Leucaenia leucacephala* species is 50% than *Pithicellobium dulce* species. Whereas net precipitation for the location is only 25%, the second point is the role of stemflow which contributes more than 40% in net precipitation. The percentage is higher than other studies in different area of the world (Murakami, 2009; Tanaka et al., 1996; Kelman and Roulet, 1990; Martinez-Meza and Whilford, 1996; Ziegler et al., 2009). Even many studies neglect stemflow contribution from their calculation (Gomez-Peralta et al., 2008). In other words the additive water source in the

Dhofar cloud forest is the fog which is strongly influenced by capturing body size and canopy properties. Moreover, the research emphasis that stemflow is an essential parameter, explains heterogeneities in net precipitation depending on tree species or height of the vegetations. Since stemflow is accumulative around vegetation stems, it is considered to be a source point which accelerates the water to subsurface faster. In the way it assumes to be a source for ground water recharge (Prada et al., 2009).

The objectives of chapter II are to measure net precipitation (stemflow and throughfall) at small-scale in a semi arid cloud forest and to have an improved understanding how net precipitation is effected by location (forest edge and forest interior) or alternatively by tree species. Moreover, the objectives of chapter III of this research are to identify sources of large infiltration fluxes from stemflow (sources point) and throughfall (dripping point) under canopy in small scale, investigate for time stability of those fluxes patterns and understand the role of outliers and their return probability. In addition, chapter IV aims to determine the lag time between rainfall events and throughfall and stemflow for two trees species (*Pithicellobium dulce* and *Leucaenia leucacephala*) and to estimate the storage capacities for stemflow and throughfall for both species

Chapter II of this research is focused on the spatial of net precipitation under canopy for two tree species located at the forest edge and in the interior of the forest in a semi arid cloud forest. Data collected from six plots for stemflow, throughfall and rainfall are used to measure at a small scale net precipitation and gain more knowledge on how it is influenced by edge and species.

Chapter III deals with heterogeneity of below canopy fluxes. In other word, water reaching the forest floor is not distributed equally from both throughfall and stemflow. The variability of canopy fluxes are measured in a small scale of 0.5 meter grid (11mx7m) under tree canopy to understand the time stability of variability patterns and to investigate the role of throughfall and stemflow outliers and probability of their return.

Chapter IV is focus on lag time between rainfall and fog events as inputs to the system and stemflow and throughfall as output parameters. Moreover, the storage capacities of canopy and stem for *Pithicellobium dulce* and *Leucaenia leucacephala* species are investigate. The two tree species plots are located at the interior of forest and equipped by an automatic logger measuring each 15 minutes.

The scarcity of the water in semi-arid regions is not only the unique factor, but also the desertification of land is an additive issue. Desertification is caused by different factors such as over-grazing, soil-erosion, rainfall-variation, etc. Hence, management of water resource in these environments is a challenge for official authorities as well as citizens. Considering the fact that water is vital for both of human and plants. Using the unique cloud forest occurrence in this part of Arabian Peninsula; conserving, managing and understanding the input water to the system is essential for further plans. Building on this view, the research tends to know how much water enters the system by determining (i) rainfall and the spatial distribution of net precipitation beneath the canopy in semi arid cloud forest due to the vegetation species and position from the edge. Hence, estimate horizontal precipitation. Moreover, to determine (ii) the lag time between rainfall and net precipitation components (stemflow and throughfall) for two trees species. The lag time leads to compute canopy storage capacity and stemflow storage capacity and (iii) to investigate temporal stability of throughfall patterns and stemflow (point sources) fluxes patterns under canopy within small scale field experiment.

The findings of the research will help in the effort of desertification combat and in re-plantation and management of enclosures; especially some enclosures failed to survive.

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# Chapter II

## Spatial heterogeneity of net precipitation due to vegetation and position effects in a cloud forest in Dhofar[1]

Plants strongly influence the water balance, particularly in arid and semiarid environments. The most obvious pathway is upward by transpiration, but also downward fluxes like net precipitation (water arriving below the canopy) are shaped by vegetation cover. By intercepting and re-channeling water within the canopy storage, plants produce a heterogeneous infiltration field, which may reflect further on soil water distribution (Durocher, 1990; Li et al., 2009; Liang et al., 2011; Pressland, 1976) and possibly on groundwater recharge (Chang and Matzner, 2000; Taniguchi et al., 1996).

In areas with frequent ground fog, canopy processes play an even more important role for shaping the patterns of water arriving at the ground (comprehensive review by Bruijnzeel et al., (2011)) and deep percolation (Liu et al., 2005) . Where a canopy is present, cloud collection by canopies may contribute substantially to the water balance, particularly in non-humid regions and might lead to local alteration of ecosystem structure (Hildebrandt and Eltahir, 2006; Hutley et al., 1997; Williams et al., 2008; del-Val et al., 2006).

It is hence desirable to understand, which factors shape downward canopy water fluxes, particularly for dry, cloud-influenced ecosystems. Cloud interception or horizontal precipitation, as it is alternatively called, is a composite of two processes, turbulent deposition and edge effect, which might both be modified by canopy properties. The edge effect refers to wind blowing cloud droplets horizontally into a canopy. This process can only be active, if an edge is present that is at forest borders or at particularly exposed canopies. The turbulent effect relies on eddies to mix water droplets from aloft into the canopy (a vertical process). This process depends on the amount of turbulence, as a function of surface roughness (and thus vegetation properties), and it should allow for cloud deposition at long distances from the edge in homogenous canopies. Studies show that the edge effect substantially increases cloud deposition (Weathers and Lovett, 1995; Ewing et al., 2009) and it is sometimes assumed to be the fundamental process in capturing fog droplets in cloud forest system. Weathers and Lovett

[1] This chapter is submitted: Abdullah Bawain, Jan Friesen, Sabine Attinger, and Anke Hildebrandt (submitted). Spatial heterogeneity of net precipitation due to vegetation and position effects in a cloud forest in Dhofar.

(1995) found that cloud deposition is a function of distance from the edge and the deposition decreases linearly toward the interior. Del-Val et al*.,* (2006) observed that tree regeneration and stand structure was associated with fog water since trees grew more at the forest edge and less at the leeward location where less fog water precipitates.

Canopies clearly influence cloud deposition at forest edges, but it is very difficult to pinpoint, how turbulent deposition is modified by canopy structure. The method used is eddy covariance measurements with considerable footprint areas, which make it impossible to measure fog deposition in the exact same climatic conditions over different vegetation cover. Theoretically, tall vegetation should induce more turbulence and capture more droplets than short one, and slick, long leaves should enable cloud capture more than big and broad ones. Although it is difficult to prove this directly in experiments for the above reasons, a collection of the observed data suggests similar trends:

The two processes (turbulent deposition and edge effect) are difficult to disentangle resulting also in different concepts and models for prediction of cloud deposition on vegetation. Some focus entirely on turbulent deposition (Shuttleworth, 1977; Slinn, 1982), others consider deposition as the integral of edge effects on individual crowns (Lovett, 1984), and others are mixtures (Hildebrandt and Eltahir, 2008). The different model types also suggest different roles of canopy properties (roughness versus individual crown exposure) for capturing cloud water. This illustrates the lack of understanding of the relative importance of canopy properties versus edge effects for shaping water availability on the ground in cloud-affected ecosystems.

So, what are the dominating processes and relevant site properties that shape net precipitation in a cloud forest environment? The heterogeneity of net precipitation (total water received below the canopy, the sum of stemflow and throughfall) makes it difficult to compare adjacent sites and thus disentangle the influence of site properties, canopy shape, and edge effects on cloud deposition and the resulting net precipitation. Furthermore, processes transferring the total received water through the canopy, such as stemflow and throughfall, also depend on canopy properties. Thus, studies at a smaller scale are required.

The purpose of this paper was to measure at the small-scale net precipitation in a cloud environment and to gain an improved understanding of how it is influenced by a sharp edge or alternatively by canopy structure (tree species). For this we used a fenced young growth forest surrounded by bare soil in the region of Dhofar in Oman. Because it is surrounded by bare soil, the sides of the enclosure express a perfect forest edge. In addition, trees within the enclosure were planted in groups of the same species, thus providing small clusters of quasi homogenous canopies, which can be compared in similar meteorological conditions. These two features combined allow us to investigate separately the influence of the edge versus canopy structure on net precipitation. Based on the literature we hypothesized that the edge plays the essential role for increasing net precipitation, and tree species would only have a minor effect. However, this hypothesis was not supported by our study. Instead we found that tree type had the strongest effect on net precipitation, and in particular through modifying stemflow.

## 2.1 Materials and Methods

### *2.1.1 Site Description*

The field study was conducted in the coastal mountain range (Jabal Al-Qara) in the Governorate of Dhofar, Oman. Dhofar is classified as a semiarid with distinct dry and wet periods. Except for a three-month monsoon season (locally called *Khareef*) that only occurs in the coastal plain and windward side of the mountains, a desert climate is predominant. Cyclones, connected to heavy rainfall (100 to 236 mm per event), occur with a frequency of 3 to 5 years (Al-Hakmani, 2006). The focus on this study is the annual monsoon season, which is the most reliable moisture source in this environment. The annual three-month monsoon season from mid-June to mid-September (Abdul-Wahab, 2003; Fleitmann et al., 2003) is characterized by heavy fog and light drizzle. Average rainfall during this period (1984-2006) amounts up to 106 mm in the coastal plain and up to 218 mm on the mountain range (Ministry of Transport and Communications, 2006). The same seasonality holds for temperature and humidity with annual averages for temperature around 26 C° in the coastal plain and 21 C° in the mountains (Ministry of transport and Communications, 2006).

Vegetation cover in the coastal plains and in the mountains consists of grass, shrubs, and trees. Tree vegetation, however, mostly occurs in the mountains. However, due to livestock pressure, most of the natural tree cover has been replaced by grass, which is now the dominating vegetation in mountain regions where it is accessible for animals. Steep slopes along the ephemeral river courses (locally called *wadis*), inaccessible for the majority of livestock, show the natural tree vegetation of the mountains.

Measurements were conducted at the Tawi Attair forest enclosure (17° 6' 42"N, 54° 31' 27"E, 650 m asl), a fenced site of about 5 hectares, located on a plateau. The vegetation outside the enclosure is dominated by grass vegetation. Data for this study were collected within an experiment site at the southeast corner (major wind direction, see inset figure 2.1) of the enclosure. The experiment site occupies a total area of 7 000 $m^2$.

Within the experiment site, six plots were delineated around tree clusters of the same species and at different positioning towards the windward edge. Of the six plots, four consist of *Pithicellobium dulce* trees (one at the edge, three in the interior, Fig 2.1(Right)) and two of *Leucaenia leucacephala* trees (one at the edge and one within the interior, Fig. 2.1(Right)). Table 2.1 gives an overview of properties and equipment of each plot. In the remainder of this paper the genus names (*Pithicellobium* and *Leucaenia*) are used to refer to the trees. For brevity, in the tables and figures we will refer to species A (*Pithicellobium*) and species B (*Leucaenia*).

Considering the size of the experimental site, climatic conditions can be assumed equal. Soil texture throughout the experimental site is characterized as clayey (survey of seven samples, data not shown) with a homogenous distribution. Sand contents around 32% (Stdev 4.1), silt around 21% (Stdev 2.5), and clay around 47% (Stdev 5.4).

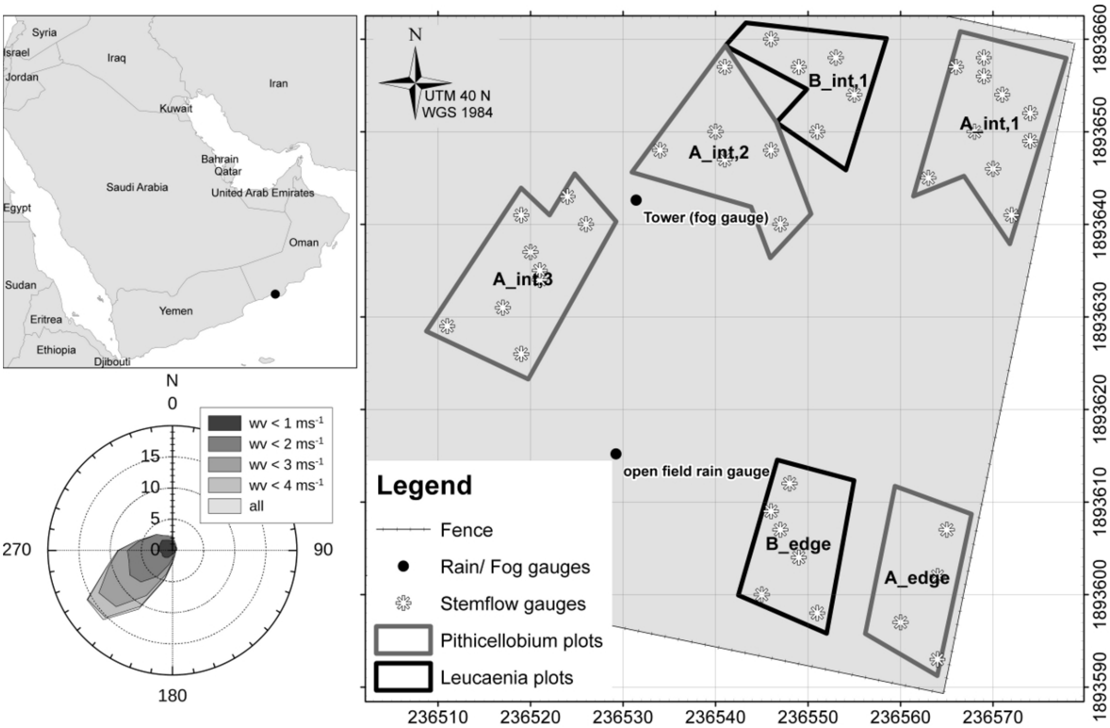


**Fig.2.1.** (Left top) Location of study area in Arabian Peninsula; (Right) Schematic of experiment plots at Tawi Attair enclosure forest; and (Left bottom) wind direction (degree) and wind speed ($ms^{-1}$).

In the six experiment plots throughfall buckets and stemflow gauges were installed, Table 2.1 shows the number of gauges in each plot. Data were read manually twice per week for the 2008, and on a daily basis for the 2009 monsoon season.

### 2.1.2 Throughfall

In total 30 collectors (5 per plot) were used to sample throughfall manually. Each collector consisted of a funnel with an 0.2 m diameter (~ 0.0314 $m^2$), connected to a 5 liter container. The collection surface was elevated 50 cm above the ground. A roving gauges method was applied to minimize the effect of spatial variability on the measurements (Frumau et al., 2006; Holwerda et al., 2006; Lloyd and Marques, 1988). That is, after each reading, the collectors were moved randomly to a new position within their plot boundaries, figure 2.1(Right). All throughfall readings were converted to millimeter per day.

### 2.1.3 Stemflow

Stemflow was sampled at altogether 40 stems from two tree species, at the six plots. Strips of 3-inch flexible plastic hoses were wrapped around the stems and fixed using super glue. At the lowest point, a pipe of 10 mm diameter was inserted and connected to a 25 liter container. Silicone sealant was used to seal the gaps between the stem and the tube strip (Hildebrandt et al., 2007). The number of stems sampled at each plot varies. Not all trees had a suitable form to allow sampling of stemflow (branching near the ground), and some of the stemflow gauges broke early in the season and could not be re-sealed during the moist season itself. Table 2.1 gives an overview of the number of stemflow gauges in each plot.

Collected stemflow volume was transferred to a flux per square meter (comparable to precipitation rate) using the following method. Within each plot, all tree stems were counted, and the following equation was used to calculate stemflow ($P_{SF}$ in mm $d^{-1}$):

$$P_{SF} = \left( \frac{V_{SF}}{n_{obs}} \right) \cdot \left( \frac{n_{tot}}{A_P} \cdot \frac{1}{\Delta t} \right) \tag{2.1}$$

Where $P_{SF}$ is the stemflow in (mm $d^{-1}$), $V_{SF}$ is the total stemflow volume (in l) collected at all gauges in this plot since the last visit, $n_{obs}$ is number of stems with stemflow gauges (-), $n_{tot}$ is total number of stems within this plot (-), $A_p$ is the plot area in ($m^2$) and $\Delta t$ is the time interval between two consecutive measurements in (d).

**Table 2.1.** Equipment and Plot Properties.

| Plot | Location | Tree species | Plot properties Area | Distance from edge Min - Max | Stems | Avg. Tree Height | Number of gauges $P_{TF}$ | $P_{SF}$ 2008/2009 | Results $P_{SF}$ / $P_{Net}$ | $P_{TF}$ / $P_{Net}$ | $P_{Net}$ / $P_{Rain}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (-) | (-) | (-) | ($m^2$) | (m) | (-) | (m) | (-) | (-) | (-) | (-) | (-) |
| $A_{edge}$ | Edge | *Pithicellobium dulce* | 147 | 2 - 20 | 16 | 6.5 | 5 | 4/4 | 0.23 | 0.77 | 0.90 |
| $B_{edge}$ | Edge | *Leucaenia leucacephala* | 150 | 4 - 21 | 29 | 9.6 | 5 | 7/7 | 0.41 | 0.59 | 1.37 |
| $A_{int,1}$ | Interior | *Pithicellobium dulce* | 204 | 49 - 70 | 21 | 6.9 | 5 | 10/10 | 0.19 | 0.81 | 0.77 |
| $A_{int,2}$ | Interior | *Pithicellobium dulce* | 191 | 42 - 63 | 26 | 6.4 | 5 | 7/4 | 0.22 | 0.78 | 0.99 |
| $A_{int,3}$ | Interior | *Pithicellobium dulce* | 224 | 24 - 47 | 33 | 6.1 | 5 | 9/9 | 0.23 | 0.77 | 0.82 |
| $B_{int,1}$ | Interior | *Leucaenia leucacephala* | 136 | 54 - 69 | 25 | 9.3 | 5 | 5/6 | 0.41 | 0.59 | 1.15 |

### 2.1.4 Fog

The fog collector used in this experiment was adapted from Fischer and Still (2007). The fog collector was mounted at a height of 7 m and fog water was drained to a 25 l container on the ground.

### 2.1.5 Rainfall

Gross rainfall was measured by using a standard rain gauge of 200 $cm^2$ funnel area, mounted 1 m above the ground in an open wind shaded area at the south-west of the site (see Figure 2.1(Right)). The gauge nozzle was connected to a 5 liter bottle. We compared several rain measurements at this site, at different elevation from the ground, shapes and orifice areas and chose the one, where measured rainfall was consistently largest.

### 2.1.6 Precipitation components

Net precipitation ($P_{Net}$ in mm $d^{-1}$), the total water received below tree canopies was calculated from throughfall and stemflow as follows:

$$P_{Net} = P_{SF} + P_{TF} \tag{2.2}$$

Where $P_{TF}$ (in mm $d^{-1}$) is the measured throughfall, apparent interception ($I_a$ mm $d^{-1}$) is an estimate of the amount of water, which is either lost or gained by canopy processes. It was calculated from the observed water fluxes above (rainfall) and below (net precipitation) the canopy (adapted from Bruijnzeel et al. (2001)):

$$I_a = P_{Rain} - P_{Net} \tag{2.3}$$

Where $P_{Rain}$ is the rainfall (mm $d^{-1}$), negative apparent interception indicates cloud capture or horizontal precipitation. Cloud capture might still be present when apparent interception is positive, but in this case, evaporation loss from the moist canopy was larger than cloud capture.

### *2.1.7 Data analysis*

#### *2.1.7.1 Data quality*

During the experiment some instrumental failures occurred, with several causes. Thus before analysis, we screened data to determine whether sufficient data points were available. In order to derive representative results for rainfall partitioning of the different experiment plots it is necessary (i) that data for all precipitation components (rainfall, throughfall, stemflow) are available for the particular observation periods, and (ii) that a minimum number of gauges per plot is functioning in order to ascertain spatially representative values.

Gauge failures for stemflow were mainly due to overflow of the collection containers. Container size was 25 liters, but during very foggy days, this was not sufficient to accommodate the daily arriving volume and more frequently than daily visits were not possible. If more than two stemflow containers overflew at a particular plot, we omitted this observation period from dataset in order to prevent underestimation of stemflow. Sometimes also stemflow gauges were blocked or throughfall gauges had tipped over. To ascertain spatial representativeness, we omitted measurement periods, when less than three gauges were operational within a given plot and period.

Based on the above-mentioned screening rules only periods with matching observation periods for throughfall, stemflow, and rainfall, as well as with a sufficient number of functioning gauges were analyzed.

#### *2.1.7.2 Statistical analysis*

Both throughfall and stemflow vary considerably in space and time. In order to account for the limited number of sampling points, bootstrap analysis was applied to derive expected values of throughfall, stemflow and calculated net precipitation (using Equation 2.2). For all measurement periods during seasons we sampled with replacement from the original data sets (Hildebrandt et al., 2007), with 10,000 repetitions. The median of the bootstrapped set was used for further analysis. Net precipitation was calculated accordingly. For each period, we sampled with replacement from the measurements of stemflow and throughfall, added the median of both re-sampled quantities and repeated this procedure 10,000 times, thus obtaining the probability density of net precipitation for that sampling period and that plot. The median of this set was used for further analysis.

In order to check, whether the observed differences in throughfall, stemflow and net precipitation, between different plots were significant, we followed the procedure given in (Davison and Hinkley, 1997), i.e.

$$p_{boot} = \frac{1+\#(E)}{R+1} \tag{2.4}$$

Where $p_{boot}$ denotes the significance probability, # ($E$) indicates the number of times, the event $E$ occurs during the bootstrapping procedure, and $R$ is the total number or repetitions, in our case $R$=10,000. We investigated, whether the plot specific below canopy fluxes (throughfall, stemflow and net precipitation) varied significantly with regard to species and location near the edge. Thus, the first events ($E$) we considered were differences in fluxes between plots located at the edge compared to those of interior plots. This was done separately for each species. For example, we asked whether species *Pithicellobium* plots near the edge had higher throughfall than species *Pithicellobium* plots in the interior *(i.e.*$E_1$: $P_{TF}(A_{edge}) > P_{TF}(A_{int,\,all})$) or if the inverse *was* true (i.e. $E_2$: $P_{TF}(A_{edge}) < P_{TF}(A_{int,\,all})$). We proceeded similarly for $P_{TF}\ (B_{edge}) <> P_{TF}\ (B_{\mathrm{int},\,1})$, and subsequently tested through all below canopy fluxes of interest. Second, we considered differences of plots with different species (separately at edge and interior location), i.e. $A_{edge} <> B_{edge}$ and $A_{int,\,all} <> B_{\mathrm{int},1}$. We considered the differences between plots as significant, when $p_{boot}$>0.975. The software R was used for the statistical analysis (R Development Core Team, 2008).

For the analysis of variance (ANOVA) one-way ANOVA models of stemflow were done using different sets of factors (Chambers and Freeny, 1992). All measurement periods with complete stemflow records were used (see Data quality). Different stemflow models were evaluated using location (factorial: edge, interior), species (factorial: *Leucainia*, *Pithicellobium*), and biomass as input data. For lack of data the product of tree height and stem circumference were used as a proxy for biomass. The different models were: M1 location+species, M2 species+location, M3 species, M4 location, and M5 location+biomass. The models were calculated separately for each measurement period using all stemflow gauges available for the respective periods. For evaluation of the different models and input data combinations r squared goodness of fit values were used. All ANOVA analyses were done using the 'aov' model as part of the 'stats' package of R (R Development Core Team, 2008).

## 2.2 Results

### *2.2.1 Precipitation components and rainfall partitioning*

Table 2.1 summarizes the precipitation components for all plots and for all complete measurement periods (28 observation periods, see Materials and Methods). On the seasonal average, net precipitation was larger in *Leucaenia* plots compared to *Pithicellobium* plots, and our data do not show a clear influence of the edge. While net precipitation was largest at an edge plot ($B_{edge,}$ *Leucaenia*), for *Pithicellobium*, the largest net precipitation was observed within an interior plot. Please note however, that although, the ratio of $P_{Net}/P_{Rain} > 1$ indicates that horizontal precipitation only occurred in plots B (*Leucaenia*), the *Pithicellobium* plots $A_{edge}$ and $A_{int,2}$ show ratios close to 1, indicating a contribution from horizontal precipitation, which is however compensated by canopy evaporation. Below, it will also be illustrated that in individual periods net precipitation was larger than rainfall even for the plot with the lowest seasonal ratio $P_{Net}/P_{Rain.}$ ($A_{int,1}$). Table 2.1 also shows differences between the precipitation components of the two species (*Leucaenia* and *Pithicellobium*), (compare $P_{SF}/P_{Net}$ and $P_{TF}/P_{Net}$), particularly for stemflow. We show below that these differences are statistically significant in many of the individual observations periods. On the contrary, at plots of the same species, the percentages of both stemflow and throughfall are relatively similar and also independent of position from the edge.

Figures 2.2a & b illustrate the different precipitation components derived for the plots where apparent interception was largest ($B_{edge}$, *Leucaenia* at the edge) and smallest ($A_{int,1}$, one of the *Pithicellobium* plots within the interior). Plotted separately are throughfall ($P_{TF}$), stemflow ($P_{SF}$), net precipitation ($P_{Net}$), apparent interception ($I_a$), rain ($P_{Rain}$), and fog are sorted by the amount of collected fog water. Although rainfall and fog are shown separately for both figures they are identical. Periods without rainfall, yet throughfall and stemflow clearly indicate horizontal precipitation (Figures 2.2a). This is obvious from both, the fact that no rainfall occurred and that apparent interception is negative ($I_a < 0$). For periods where both fog and rainfall occur this clear partitioning into the water source (i.e. horizontal precipitation or rainfall) cannot be stated. Apparent interception for mixed periods can only indicate, whether the horizontal precipitation component was substantial or not. Although apparent interception in Figure 2.2b (plot $A_{int,1}$) is much less frequently negative than in Figure 2.2a (plot $B_{edge}$), some periods exist where apparent interception becomes negative even there. This indicates that occasional cloud capture occurred also in plot $A_{int,1}$, although on the seasonal average water loss by apparent interception was significant (23%, see Table 2.1).

Since soil water flow reacts instantaneously to water input, cloud capture might periodically have contributed to the water budget, although the seasonal summary suggest otherwise.

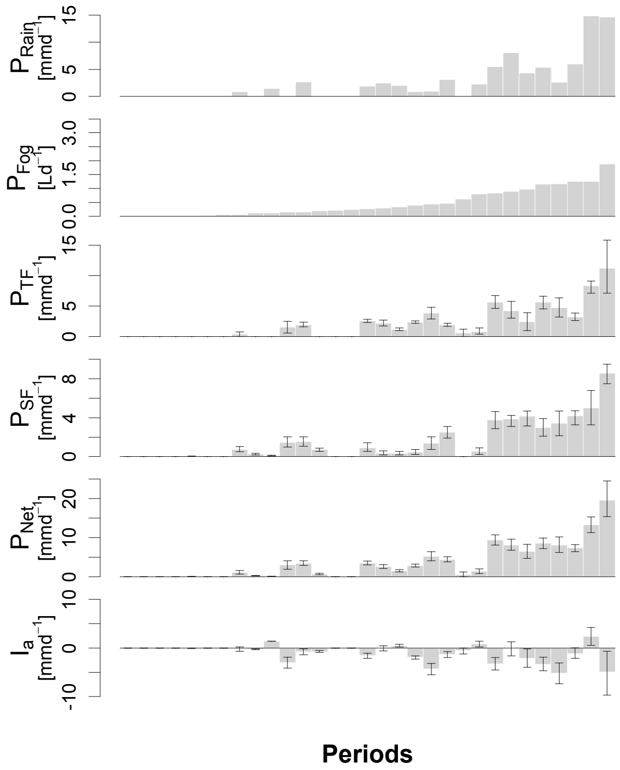


**Fig. 2.2a.** Example of rainfall, collected fog, stemflow, throughfall, calculated net precipitation (Equation 2.2) and apparent interception (Equation 2.3); positive is horizontal precipitation and negative is interception loss for plot $B_{edge}$ (*Leucaenia*). The error bars indicate the uncertainty bounds (0.05 and 0.95 quantile) derived from the bootstrap analysis.

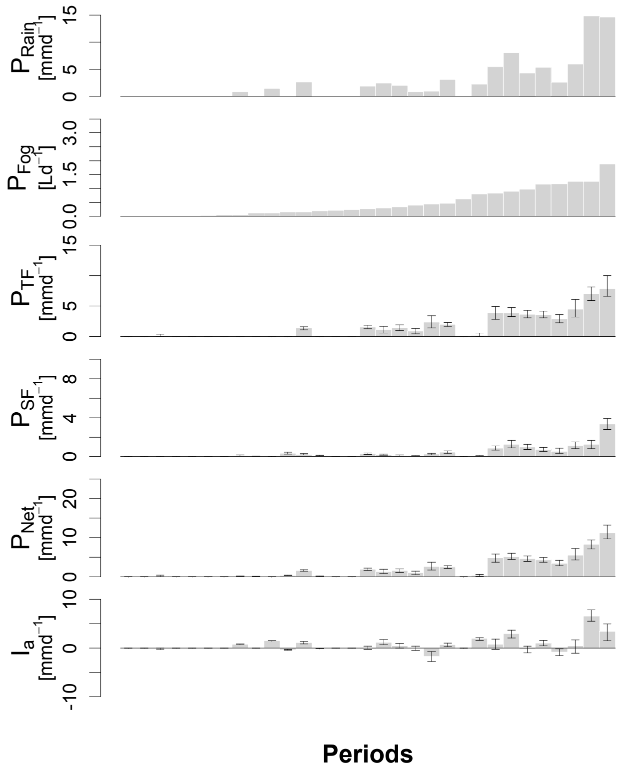


**Fig. 2.2b.** Example of rainfall, collected fog, stemflow, throughfall, calculated net precipitation (Equation 2.2) and apparent interception (Equation 2.3); positive is horizontal precipitation and negative is interception loss for plot $A_{int,1}$ (*Pithicellobium*). The error bars indicate the uncertainty bounds (0.05 and 0.95 quantile) derived from the bootstrap analysis.

Comparing plots $B_{edge}$ (*Leucaenia*) and $A_{int,2}$ (*Pithicellobium*) figures 2.2a & b further show that, whereas throughfall is relatively similar between these plots, stemflow is about twice as large in plot $B_{edge}$ than in plot $A_{int,2}$. As rainfall is the same for both, stemflow is the cause for striking difference in net precipitation and apparent interception. This fact is further supported by Figure 2.3, which shows histograms of stemflow and throughfall percentages for all plots, but separated by species *Leucaenia* and *Pithicellobium*. Throughfall for both species shows similar histograms. However, events with elevated stemflow events occur more frequently in *Leucaenia* plots (B - plots). This feature will be further investigated in the next section.

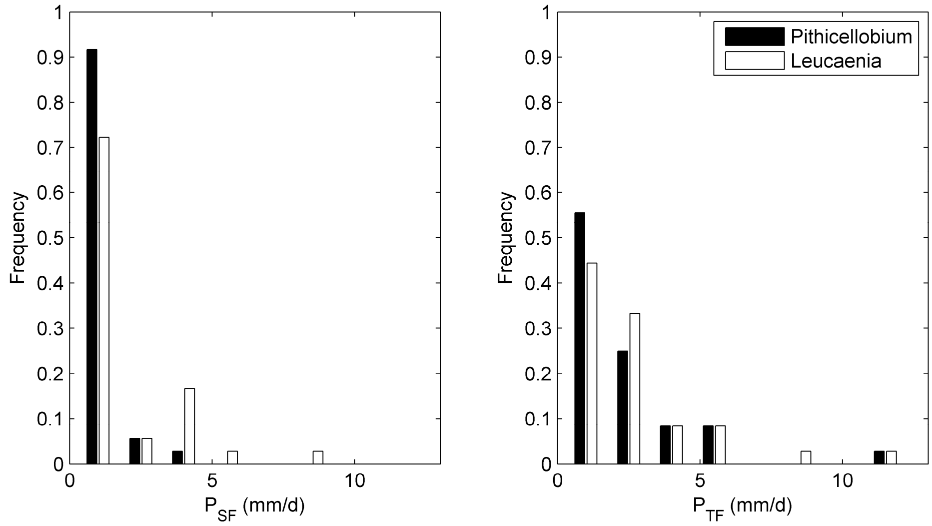


**Fig.2.3.** Histogram of stemflow and throughfall for *Pithicellobium* and *Leucaenia*

### *2.2.2 Species and location differences*

To determine what influence location and species have on stemflow, throughfall and net precipitation, we calculated how often (in how many periods), the observed differences between the plots were statistically significant. Table 2.2 summarizes the obtained occurrences (as percent of the total number of measurement periods). The test cases are divided into location effects (i.e. between interior locations and edge locations and same species, such as $A_{egde} > A_{int,\ all}$), and species effects (i.e. between *Leucaenia* and *Pithicellobium* at the same location, such as $A_{egde} > B_{edge}$).

**Table 2.2.** Effect of species and of location on throughfall, stemflow, and net precipitation

| | cases | $P_{SF}$ Periods (% )* | $P_{TF}$ Periods (% )* | $P_{Net}$ Periods (% )* |
|---|---|---|---|---|
| Species | $A_{edge} > B_{edge}$ | 0 | 7 | 0 |
| | $B_{edge} > A_{edge}$ | 75 | 39 | 54 |
| | $A_{int,\ all} > B_{int,1}$ | 0 | 4 | 0 |
| | $B_{int,1} > A_{int,\ all}$ | 82 | 25 | 50 |
| Location | $A_{edge} > A_{int,\ all}$ | 4 | 7 | 7 |
| | $A_{int,\ all} > A_{edge}$ | 0 | 18 | 0 |
| | $B_{edge} > B_{int,1}$ | 14 | 25 | 25 |
| | $B_{int,1} > B_{edge}$ | 0 | 29 | 4 |

* = percentage of measurement periods during which the observed differences, such as $A_{edge} > B_{edge}$, were statistically significant

For the species effects (Table 2.2, species) we can see that for stemflow *Leucaenia* is significantly higher than *Pithicellobium* in most measurement periods (~ 80%). Although less frequently, the same also holds true for throughfall (~ 30%) and net precipitation (~ 50%).
Regarding the edge effect (Table 2.2, location) we cannot detect similarly frequent significant differences between plots as with species. Stemflow at edge locations is elevated compared to the interior somewhat more frequently (max 14 % of the periods), but the effect is not as dominant as the species effect (75% of the periods). For throughfall (~25% both at the edge and the interior), however, both locations are balanced with no clear tendency towards one location yielding more throughfall.
Thus, significant differences were more often observed between plots of different species and less often between plots at different position from the edge (edge versus interior). Additionally, stemflow was the component that showed the most consistent difference pattern, while throughfall was ambiguous.

### *2.2.3 Factors influencing stemflow*

The influence of tree height and stem circumference on stemflow is shown in Figure 2.4. Total stemflow of each stemflow gauge for selected periods is plotted. The different symbols also distinguish species and location of each stemflow gage. Note that tree height is clearly cross-correlated with species (*Pithicellobium* is smaller than *Leucaenia*), which leads to the clusters in the scatter plot Fig. 2.4a. Both tree height and stem circumference show no clear correlation with stemflow.

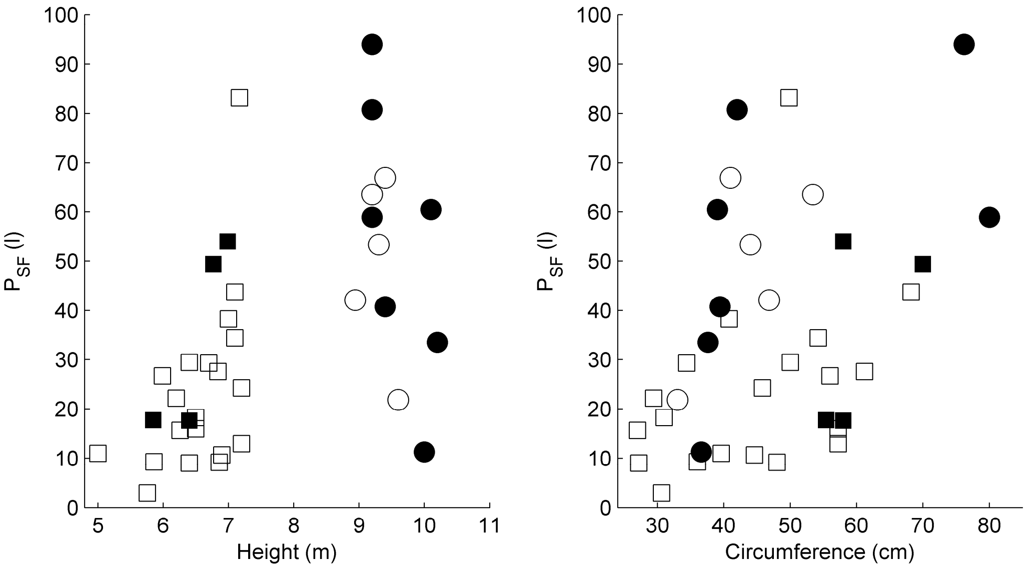


**Fig.2.4.** (a) Sum of stemflow (l) versus tree height (m); (b) Sum of stemflow (l) versus tree circumference (cm), experiment plots of *Pithicellobium* locate at the edge of the forest (black square), experiment plots of *Pithicellobium* locate at the interior of the forest (white square), experiment of *Leucaenia* locate at the edge of the forest (black circle) and experiment plots of *Leucaenia* locate in the interior of the forest (white circle).

In order to investigate this further, we conducted an ANOVA analysis, using the product of circumference and tree height as a proxy for tree biomass and therefore the crown extent. Models using tree height and circumference separately did not yield significant relations for any of these factors. Using different ANOVA models (see Table 2.3) the influence of species, location, and biomass (the product of height and circumference as a proxy for biomass) on stemflow is illustrated. Table 2.3 shows the ANOVA model performance (expressed through r squared) for different models and different measurement periods. For measurement periods with significance levels below 0.05 r squared is not shown. Models where species is the main or only factor (Table 2.3, M2, M3, M5) show significant relations more frequently (18-20 significant periods) than models where location is the main factor (Table 2.3, M1, M4) (13 significant periods). Overall, the model using species as the first factor and biomass as the second shows significant correlation with stemflow during most periods and has the highest r squared values.

**Table 2.3.** Goodness of fit (r squared) for different ANOVA[a] models predicting stemflow.

| Period | M1<br>Location + Species | M2<br>Species + Location | M3<br>Species | M4<br>Location | M5<br>species + biomass |
|---|---|---|---|---|---|
| 1 | 0.47*[b] | 0.47 | 0.46 | 0.17 | 0.48 |
| 2 | 0.59* | 0.59* | 0.52 | 0.29 | 0.57 |
| 3 | 0.42* | 0.42 | 0.42 | 0.13 | 0.44 |
| 4 | 0.47* | 0.47 | 0.43 | 0.23 | 0.57* |
| 5 | 0.44* | 0.44 | 0.39 | 0.21 | 0.46 |
| 6 | 0.28* | 0.28 | 0.22 | 0.18 | 0.70* |
| 7 | [c] | 0.24 | 0.24 | | 0.42* |
| 8 | 0.40* | 0.40 | 0.33 | 0.22 | 0.69* |
| 9 | | | | | |
| 10 | 0.30* | 0.30 | 0.24 | 0.18 | 0.51* |
| 11 | 0.35* | 0.35 | 0.30 | 0.20 | 0.61* |
| 12 | | 0.15 | 0.12 | | 0.12 |
| 13 | | 0.31 | 0.30 | | 0.62* |
| 14 | | 0.33 | 0.33 | | 0.51* |
| 15 | | 0.32 | 0.31 | | 0.57* |
| 16 | 0.46* | 0.46 | 0.44 | 0.19 | 0.52* |
| 17 | 0.36* | 0.36* | 0.26 | 0.25 | 0.49* |
| 18 | 0.20* | 0.20 | | 0.18 | 0.18 |
| 19 | | | | | |
| 20 | | | | | |
| 21 | | | | | |
| 22 | | | | | |
| 23 | | | | | |
| 24 | | 0.19* | 0.18 | | 0.31* |
| 25 | | | | | |
| 26 | | | | | 0.32* |
| 27 | 0.27* | * | | 0.25 | |
| 28 | | 0.17 | 0.17 | | 0.17 |
| 29 | | | | | |
| 30 | | | | | |

[a] For analysis the ‘aov’ model in the ‘stats’ package of R (reference) was used.
[b] * indicates that the second parameter was significant (alpha = 0.05).
[c] Periods with no value indicate that the ANOVA model was not significant (alpha = 0.05).

## 2.3 Discussion

The Tawi Attair site is an ideal location for investigating the heterogeneity of net precipitation originating from possible edge and trees species effects in the semiarid zone. The experiment was conducted at a small scale and for two tree species in an isolated area. Each tree species occurs in clusters and are investigated in separate plots. In addition, the soil of all experiment plots is homogenous (clayey soil). The small-scale experiment minimizes the variation due to external factors, such as climatic differences, and allows for investigating the role of location and tree species on net precipitation. In contrast, studies on net precipitation in cloud-affected ecosystems usually do not deal with species differences (i.e. studies reviewed in (Bruijnzeel et al., 2011)).

At the start of this research we hypothesized that the tree edge would play an important role for shaping net precipitation in this cloud environment, and tree species would play a secondary role. Surprisingly, we found that species played a more important role for explaining observed differences in net precipitation, and more surprisingly even, most of the variation was due to differences in stemflow. Whether stemflow or throughfall or both modify net precipitation, is not only an academic question, because those processes have different implications for patterns of soil moisture and expected groundwater recharge (Levia and Frost, 2003).

How can this be explained? We believe there are two alternative processes, which could lead to the observed pattern: (a) *Leucaenia* intercept more cloud water, likely because of their larger canopy or (b) *Leucaenia* and *Pithicellobium* intercept similar amounts of cloud water, but the branch and trunk structure of *Leucaenia* allows for faster draining of the canopy and smaller interception losses in the period anteceding the precipitation event. As a third alternative (c), it could be argued that tree density (a larger number of trees) influences the calculated amount of stemflow, but our results do not support the latter: Tree density plays an important role for calculating the equivalent precipitation height calculated from stemflow, because of equation 2.2. However, the average tree density of the *Pithicellobium* plots ($A_{int,1}$+$A_{int,2}$+$A_{int,3}$) is 0.386 $m^{-2}$, and therefore bigger than the tree density of the corresponding *Leucaenia* plot, which is 0.184 $m^{-2}$. Yet overall, *Leucaenia* plots receive more equivalent stemflow. It is the stemflow volume collected by individual trees, which is much larger in *Leucaenia* compared to *Pithicellobium*. Thus, we are left with hypotheses (a) and (b). We are unable to fully resolve the relative importance of these with our data, but we believe that process both processes (a) and (b) are active, for the reasons explained in the following.

The canopy structure features of *Leucaenia/Pithicellobium* might decrease/enhance stemflow and at the same time inversely affect the interception loss from wet canopy. Figure 2.5 shows the differences in trunk structure and branching of the two species. Both species bark structure is comparatively smooth, which probably leads to the overall large stemflow proportions found in this study. However, the bark of *Pithicellobium* is characterized by horizontal line structures (Fig 2.5a), while the lines in the bark of *Leucaenia* are vertical and in the direction of stemflow (Fig 2.5c). Furthermore, the branches of *Leucaenia* are also steeper than those of Pithicellobium (Fig 2.5b vs. Fig 2.5d), probably leading to fewer drip points and more continuous flow paths. Crown architecture, branching patterns, bark features, and leaf form determine how much water remains on leaves, branches, and bark, and thus how long water is retained after a precipitation event.  The longer water stays on leaves and branches, the higher is the probability for water to evaporate back to atmosphere after the end of the precipitation event (Crockford and Richardson, 2000). From visual inspection the bark storage of *Leucaenia* seems to be lower than the one of *Pithicellobium*, which probably allows for more efficient drainage of the canopy. Thus, plots of *Pithicellobium* might have lost more water to evaporation from wet canopy than *Leucaenia*.


**Fig. 2.5**. Pictures of trunk (top) and crown (bottom) structure of the two tree species under investigation: *Pithicellobium* (left) and *Leucaenia* (right).

The results of the ANOVA analysis indicate that species identity is the most important property modifying stemflow, while within species the individual size of the trees influences this flux. We are unable to resolve, whether the overall larger biomass of *Leucaenia* dominates this effect and allows for more cloud capturing, or whether the larger crowns simply increase stemflow. However, our result is in accordance with observations made in mostly cloud free ecosystems, which suggests that increased cloud capture is not a necessary pre-requisite to explain our results. An increase of stemflow with increasing biomass has been observed in other forests (Deguchi et al., 2006; Garcia-Estringana et al., 2010; Germer et al., 2010). Stemflow is created when precipitation interacts with the tree wood (Crockford and Richardson, 2000), and if the bark is sufficiently conductive, larger wood structure should increase stemflow per se, independent of cloud capture. The stemflow of *Leucaenia* is almost double of the stemflow of *Pithicellobium*. These proportions are the same in the years 2008, 2009, and also 2010 (data not shown) as well as at each location (interior and edge). Stemflow is around 20% of net precipitation in *Pithicellobium* and 40% in *Leucaenia*. These constant proportions suggest that species identity determines this proportion, which is in accordance with results from a (non-cloud influenced) forest, where between species differences in stemflow were larger (likely due to bark structure), while within species differences were explained by tree size (Levia et al., 2010) . Also Andre et al. (2008) also observed species differences in stemflow, and studies suggest that bark structure plays a fundamental role for differentiating stemflow between species (Barbier et al., 2009; Stan and Levia, 2010) .

Few studies investigated species differences in partitioning net precipitation into throughfall and stemflow for the above-mentioned reasons. In a review of net precipitation in Mediterranean ecosystems, throughfall was found to be species specific in trees (opposed to our study, where it is similar), and species influence in stemflow was only found for shrubs (Llorens and Domingo, 2007). On the other hand, Kraemer and Hoelscher (2009) found that stemflow proportion was often related to the proportion of certain tree species (ash and beech). In their study, proportions of stemflow and throughfall changed in opposite ways with species composition, such that total interception was constant between plots. This is in contrast to our study, where throughfall remained constant while stemflow changed between plots of different species such that an increase in stemflow had a net effect on interception (which even switched signs between plots, i.e. cloud capture).

The latter could be an indication that cloud capture differences in cloud capture did play a role in our study. However, the reason for the observed dependence of stemflow on species and congruent contribution to apparent interception in our study may also be grounded on the low precipitation intensities, characteristic for the monsoon rain in Dhofar. When precipitation intensities increase, stemflow is expected to increase until a certain level, when stemflow paths become overloaded and the water drips to the ground. Thus, stemflow saturates to a maximum level with increasing precipitation, while throughfall keeps increasing (Andre et al., 2008; Crockford and Richardson, 2000; Staelens et al., 2008). Thus, one would expect for throughfall/stemflow ratio to become large at higher rainfall intensities (Crockford and Richardson, 2000), which would lead to obliterating differences between plots (which was also observed by Andre et al. (2008) in a cloud free environment). In our case, overloading of stemflow pathways is probably seldom; hence species differences are more pronounced. Additionally, the bark is probably efficiently wetted during fog events, since the precipitation angle is almost horizontal, which is known to promote stemflow (Crockford and Richardson, 2000). This should allow for stemflow paths to become active at comparatively low intensity rainfall. It is also likely, that the sturdy branches and twigs are more efficient fog catchers than leaves, and hence fog capture is more readily transformed to stemflow than throughfall. Our data do not yet allow investigating these hypotheses. However, since stemflow is a very efficient flow path leading to infiltration hotspots in a water scarce region, further investigation of processes involved in creating and modifying stemflow are warranted.

Our results confirmed previous research (Weathers and Lovett, 1995; del-Val et al., 2006) in that areas near the forest edge receive more water than interior areas, when comparing plots composed of the same species. However, as stated above, the differences between species were more often significant. At the seasonal scale, only for *Leucaenia* we observed a net gain of water below the tree canopy ($P_{Rain}<(P_{Stem}+P_{TF})$) both at the edge and in the interior, whereas for the other species *Pithicellobium,* less water was received below the trees than above. Thus, the interior plot of *Leucaenia* received more net precipitation than the edge plot of *Pithicellobium*. This is although the exposed area of *Pithicellobium* trees at the forest edge is considerable (average tree height in the edge plot is 6.5 m), and much larger than the exposed crown tops of *Leucaenia* protruding over the ones of *Pithicellobium* within the interior (in the interior *Leucaenia* is on the average 2.8 m taller than *Pithicellobium*). As mentioned above, the important variable modifying net precipitation was stemflow (throughfall was ambiguous). At the same time, we only a found weak relation between tree size matrices (tree height and diameter at breast height as proxy for crown size) and stemflow. Thus, crown exposure above the surrounding canopy was probably not an important influence on net precipitation.

Overall, stemflow is very large in this region, which has already been observed by Hildebrandt et al. (2007), but they are in the range of stemflow measured in semiarid regions (Levia and Frost, 2003). In a review on cloud forests hydrology by Bruijnzeel et al. (2011), the cloud forest receiving least mean annual precipitation is in Hawaiian (Juvik and Nullet, 1995) with 500 mm/a, which is still more than double the annual precipitation received in the Dhofar mountains about 218 mm (Ministry of transport and communications, 2006). The semiarid climate, as well as the obtuse angle of the light precipitation (drizzle and cloud droplets) might enhance stemflow by efficient wetting of the tree stems (Crockford and Richardson, 2000). In water-limited ecosystems, where often periods of rainfall and sunshine succeed each other in short intervals, stemflow might be an efficient mechanism for conducting water quickly into deeper soil layers, where it is safe from evaporation (Li et al., 2009). Thus, trees with characteristics conducive to increasing stemflow might have higher chance for surviving harsh drought conditions, by efficiently harvesting the little available water.

In our study we show that *Leucaenia* apparently has competitive advantage over *Pithicellobium*. Although both trees were planted at the same time, *Leucaenia* is overall 3 m taller than *Pithicellobium*, which might be due to a feedback with its capacity to efficiently harvest precipitation. However, *Leucaenia* is also a known invasive species (Gordon et al., 2011). Thus in spite of these positive characteristics, its application should be considered with care.

## 2.4 Conclusion

Heterogeneity of net precipitation in semiarid region cloud forest was studied during two consecutively seasons (2008 and 2009) for two tree species *Leucaenia* and *Pithicellobium*. It is found that tree species plays an essential role in effecting the heterogeneity net precipitation, which is more important than the edge effect at the Tawi Attair enclosure. Moreover, stemflow in this environment is found to be an important pathway for channeling water to the ground and modifying available water in the plots of different species. Therefore, stemflow could play important role as point source for groundwater recharge. In addition, the fractional of throughfall and stemflow is constant at the edge and at the interior of the forest for both species (*Pithicellobium* and *Leucaenia*). This proves the importance of tree species than the location on the heterogeneity of net precipitation. *Leucaenia* tree species is found to capture more horizontal precipitation than *Pithicellobium*.

Our study emphasizes that tree species effects can play a role comparable or even more important than the more often cited edge effect for shaping net precipitation in cloud forests.

**Table 2.4.** Symbols used in chapter two

| Symbol | Description | | Value/Units | Equation |
|---|---|---|---|---|
| $P_{TF}$ | Throughfall of the plot | $LT^{-1}$ | mm $d^{-1}$ | 2 |
| $P_{SF}$ | Stemflow of the plot | $LT^{-1}$ | mm $d^{-1}$ | 1, 2 |
| $n_{obs}$ | Number of measured stems | - | - | 1 |
| $n_{tot}$ | Total stems number within a plot | - | - | 1 |
| $A_P$ | The plot area | $L^2$ | $m^2$ | 1 |
| $t$ | The Time between two consecutive measurements | T | d | 1 |
| $P_{Net}$ | Net Precipitation | $LT^{-1}$ | mm $d^{-1}$ | 2,3 |
| $P_{Rain}$ | Gross Rainfall | $LT^{-1}$ | mm $d^{-1}$ | 3 |
| $I_a$ | Apparent interception | $LT^{-1}$ | mm $d^{-1}$ | 3 |
| $p_{boot}$ | Significance probability | | - | 4 |
| $\#(E)$ | Number of times, the event $E$ occurs during the bootstrapping procedure | | - | 4 |
| $R$ | Total number or repetitions | | 10000 | 4 |
| $A_{edge}$ | Plot (*Pithicellobium dulce*, edge) | | | |
| $A_{int,1}$ | Plot (*Pithicellobium dulce*, interior) | | | |
| $A_{int,2}$ | Plot (*Pithicellobium dulce*, interior) | | | |
| $A_{int,3}$ | Plot (*Pithicellobium dulce*, interior) | | | |
| $B_{edge}$ | Plot (*Leucaenia leucacephala*, edge) | | | |
| $B_{int,1}$ | Plot (*Leucaenia leucacephala*, interior) | | | |

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# Chapter III

## What causes below canopy heterogeneity of water fluxes?[2]

Ground water recharge in areas with little precipitation is assumed to be negligible, since the water, which falls on the ground returns back to the atmosphere quickly, either through direct evaporation or via plants through transpiration. Natural vegetation seems to be adapted to making optimal use of the available water, when it is limiting. For example, recharge under natural vegetation in semiarid environments is much smaller than under crops in the same areas (Llorens and Domingo, 2007). Local recharge pathways are very important in those areas (Scanlon et al., 2006), and plants might also contribute to those, by concentrating rain water in stemflow and throughfall drip-points (Keim et al., 2005; Li et al., 2009; Tanaka et al., 1996).

Precipitation partitioning among stemflow and throughfall strongly effects the spatial variation of water arriving at the soil, the soil moisture and presumably also soil water fluxes. This heterogeneity is even more pronounced in drier environments than in humid ones and it has been argued that this vegetation induced heterogeneity may create pathways of fast soil water flow (Johnson and Lehmann, 2006; Taniguchi et al., 1996). This could be a potential pathway of ground water recharge, since it enables water to quickly bypass shallow soil layers and become inaccessible both for evaporation and root water uptake. In arid environments much of the groundwater recharge has been attributed to local processes and preferential flow (Scanlon et al., 2006). Thus, understanding spatial heterogeneity induced by vegetation may help investigate potential pathways of ground water recharge.

Much research has already been invested in understanding, which canopy properties are associated with water arriving at preferential points at the forest ground. The two relevant below canopy fluxes are stemflow and throughfall. The ratio between these two fluxes and the proportion of rainfall to net precipitation (the sum of throughfall and stemflow) depend both on meteorological conditions and canopy properties (Crockford and Richardson, 2000; Llorens and Domingo, 2007). For example, canopy properties and exposure influence stemflow and throughfall fractions. Stemflow is facilitated, when the bark is smooth, leaf area is small, wood is exposed, and branch angles are steep (Crockford and Richardson, 2000). Crown morphology also plays a crucial role for throughfall. It increases with canopy gap

[2] This chapter is a submitted manuscript as: Anke Hildebrandt, Abdullah Bawain, Jan Friesen. What causes below canopy heterogeneity of water fluxes?. submitted

fraction and tree diversity (Kraemer and Hoelscher, 2009). Additionally, Herwitz and Slye (1995) concluded from a modeling study that exposed tree crowns (tall trees) should collect more water then their neighbors, while limiting throughfall in neighboring smaller trees by creating local rain shadows (Herwitz and Slye, 1995). Also leaf phenology influences throughfall. And finally, species composition affects both throughfall (Norden U, 1991) and stemflow (Kraemer and Hoelscher, 2009; Llorens and Domingo, 2007; Stan, 2010) whereas effect on stemflow seems stronger (Kraemer and Holscher, 2009; Llornes and Domingo, 2007).

Since stemflow is a concentration of water flow to a single point, infiltration rates can be locally increased and with roots potentially facilitating the flow (Johnson and Lehmann, 2006). This pathway seems likely to allow for particularly deep infiltration in arid environments (Li et al., 2009; Martinez-Meza, 1996; Pressland, 1976) but locally also modifies flow paths in humid environments (Liang et al., 2011). Because of this, stemflow might contribute more than proportionally to ground water recharge. For example, Tangiguchi et al. (1996) derived from tracer experiments, that stemflow contributed 11-19% to groundwater recharge, although it constituted only 1% of below canopy available water.

Besides canopy properties, meteorological conditions modify stemflow and throughfall fractions. For example, stemflow is expected to be larger for low rainfall intensities since stemflow does not increase proportionally to rainfall, probably because at larger rainfall rates stemflow paths become saturated and dripping point develop (Crockford and Richardson, 2000). Throughfall behaves the opposite way, because leaves are not strong enough to intercept large drops with high terminal velocities (Calder, 1996), and thus at high rainfall intensities more water reaches the forest floor. Overall less water passes the canopy at low rainfall intensities (Calder, 1996) and with increasing vapor pressure deficit (Staelens et al., 2008), probably due to larger evaporation loss, and larger proportion of canopy storage compared to the event rainfall amount.

The intriguing feature of cloud forests is that the interception loss can become a gain, because of cloud capture accompanied by low evaporation. It is therefore believed that cloud forests in the tropics contribute substantially to ground water recharge. Or in more arid environments clouds enable the survival of lush vegetation (Hildebrandt and Eltahir, 2006; Hutley et al., 1997; Juvik and Nullet, 1995). The latter seems the case for the cloud forests in Dhofar, where annual rainfall is as little as 300 mm. Hildebrandt and Eltahir (2007) concluded that the forests could only survive because they were able to use most of the incoming water for transpiration, while they concluded that in a normal year ground water recharge should be zero (something which has been observed in other semiarid areas). However, observation of spring discharges and ground water levels in the connected aquifers strongly suggest that ground water recharge does take place during almost every year (Al-Mashaikhi, 1997). Hence, the question arises, which are the related processes, and how does vegetation cover modify them.

## 3.1 Materials and Methods

Our field site is located in the South of Oman (Governorate of Dhofar) on a coastal mountain range (Jabel Al-Qara), at an elevation of 650 m. The climate is hot and dry with a distinct moist monsoon and cloud season in the summer month (mid June to mid September). The monsoon is the most reliable water source in this otherwise desert like environment. Additionally, cyclones cause heavy rainfall in an erratic fashion, about every 2-4 years. During the monsoon season stable onshore winds transport continuously moist air from the ocean towards the coastal plane, which is subsequently pushed up against the coastal mountains, leading to persistent orographic fog formation, light drizzle and rain. This annual monsoon climate allows for lush vegetation in the mountain ranges, although annual average precipitation is less then 300 mm at any station within the mountains at an annual temperature of 21 – 26 degree Celsius.

Our field site is located within a fenced re-forested area. The fence prevents grazing animals from entering. The surrounding region is almost devoid of trees (due to overgrazing), although tree cover had been common there before the 1970s. Overgrazing by increased number of animals has led to reduction of tree cover. In the 1990s efforts were undertaken be the local ministry of agriculture to re-forest this area, and trees within our site have now reached a height of up to 5-7.5 m.

We measured stemflow in 2009 and small-scale throughfall was measured for the same species in a adjacent area in 2010. It was not possible to measure the small-scale variation of throughfall and stemflow at the same time at reasonable effort. Some tests show that events in 2009 and 2010 are comparable (Figures 1 and 2). Figure 1 shows that the histograms of events sampled in 2009 and 2010 are similar: Most events are smaller then 10 mm/day (80% in 2009 and 75% in 2010), with the median being at around 3 mm/day in both years.

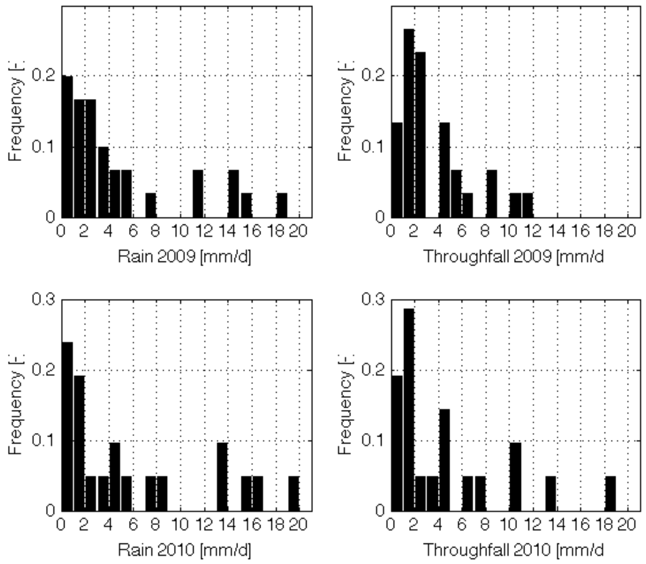


**Figure 3.1.** Histogram of the events sizes measured for rain (left column) and throughfall (right column) in the years 2009 (top row) and 2010 (bottom row).

Figure 3.2 shows that the relation between rain and throughfall was similar in both years and locations. A t-test confirms that the regression slope fitted on data in both years is significantly different from zero.

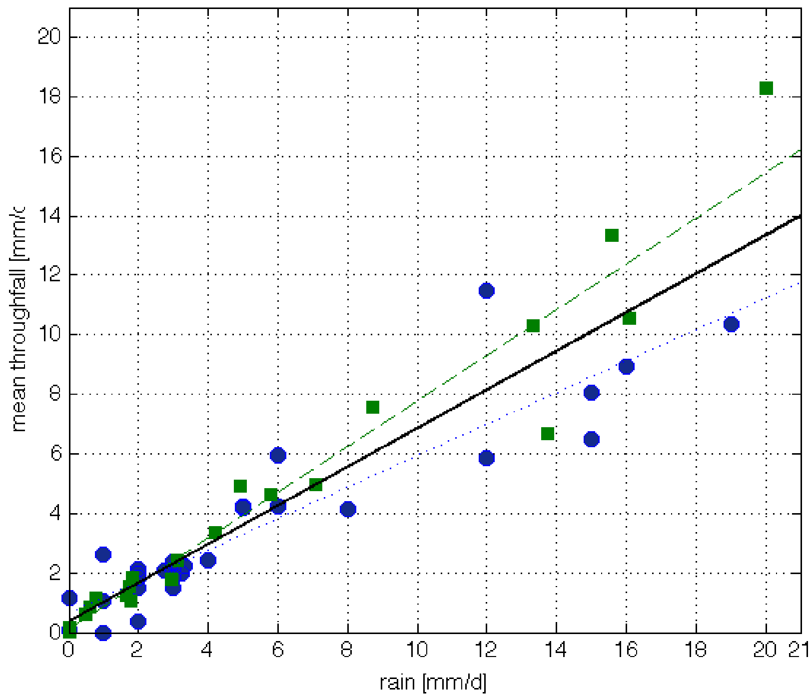


**Figure 3.2.** Relation between daily rainfall and throughfall in years 2009 (blue circles) and 2010 (green squares). The light lines give the regression lines for 2009 (blue dotted line, slope 0.53, intercept 0.65 mm/d, $r^2$=0.84) and 2010 (green dashed line, slope 0.77, intercept 0.09 mm/d, $r^2$=0.93). The heavy black line gives the regression for the combined (2009 and 2010) dataset (slope 0.65, intercept 0.37, $r^2$=0.86).

Stemflow was measured with a plastic hose wrapped around the tree, sealed with silicone and drained by a plastic pipe into a 25 l container. We sampled altogether 26 trees of various sizes within clusters of the same tree species (*Pithicellobium dulce*) in the interior of the experimental site. Sometimes, containers were too small to accommodate all water flowing down the trees within a day, thus limiting the size of observable events. We considered the event size of too large, when more than three containers had over flown. This limited our observations to events of daily throughfall of less than 7 mm /d.

In concert with stemflow measurements average throughfall was measured with a roving gauge system consisting of 15 buckets in 2009. For this funnels (A=314 $cm^2$) were mounted 50 cm above the ground and connected to a 5 l container. The collected amount was measured at the same time as stemflow. At each visit the throughfall containers were moved by at least 1m in any direction with the plot. This procedure reduces the influence of spatial heterogeneity of throughfall on the results, but on the other hand, it does not allow for sampling the heterogeneity, because repeated measurements at the same spot are not taken. The average received throughfall was calculated by bootstrap from the sample (see Chapter II).

Sampling of spatial heterogeneity of throughfall was conducted during the monsoon 2010. We defined a square (7 m x 11 m, see Figure 3.3), and distributed 65 throughfall funnels over it. The square was located within the area, where throughfall and stemflow measurements had been conducted in 2009. It contained three trees, and areas of dense canopy as well as canopy gaps. The containers were placed in the center points of a grid with 50 cm spacing. In order to avoid the influence of seasonal variation, we measured throughfall during two periods, one at the beginning of the monsoon season, during leaf flush (20 July to 27 July 2010) and at the end of the monsoon (August 23 – September 3 2010). The content of the containers was measured at daily intervals. Since canopy cover might influence throughfall, we used a weighted average of throughfall for comparison with stemflow. We calculated the arithmetic mean of throughfall for each canopy class and found the expected value by weighing each of the means by the proportion of the canopy class they represented.
For estimate the canopy cover at this small scale, we used a heuristic method. An expandable pipe was held up exactly vertically at the centre point of each grid, and the number of distinct twigs and branches touching the pipe were counted. When the canopy was very dense, only one count per 10cm was recorded. The counting was performed by the same person for the area in order to assure consistency.

**Figure 3.3.** Picture of throughfall measurements setup (7m X 11 m) with 0.5 m grid

Rainfall was measured at a wind-protected open area with a standard rain gauge in 2009, and with an automatic rain gauge at the same location in 2010. The rain gauge is elevated 1m above the ground level to avoid splash from the ground and influence of surrounding herbaceous vegetation. During the monsoon the vegetation grows tall, such that the elevation of the rain gauge is only about 20 cm above the herbaceous canopy level, and simulates well the water received at this level. Herbaceous vegetation below the trees is however much lower, probably because of light limitation.

In order for below canopy fluxes to produce deep reaching patterns of soil water flow, probably leading to groundwater recharge, those fluxes not only have to be heterogeneous in space, but those patterns also have to be persistent in time. A common technique for investigating such time stability is the production of time stability plots. For this, the mean relative difference ($\delta$) between the water collected at a certain point (index $1\leq i\leq n$,) and the event median taken over all measurement points was calculated. For example for throughfall n=65 collectors and $\delta_{TF,i} = \frac{P_{TF,i} - \overline{P_{TF}}}{\overline{P_{TF}}}$ was calculated for each of the 21 available events.

The value for $\delta_{TF,i}$=0 implies that the collector i collected exactly according to the event median, while $\delta_{TF,i}$=1 implies that the collector received exactly twice as much water as the event median. The same procedure was used for estimating $\delta_{SF,i}$ for time stability of stemflow.

## 3.2 Results

Since rainfall and throughfall events sizes for the two seasons (2009 & 2010) were similar (Figure 3.1), we assume that the relation between rainfall and below canopy fluxes did not change between years. This is also supported by Figure 3.2. The majority of rainfall event sizes were between 0 and 6 mm per day and throughfall events size were between 2 and 5 mm per day in both years.

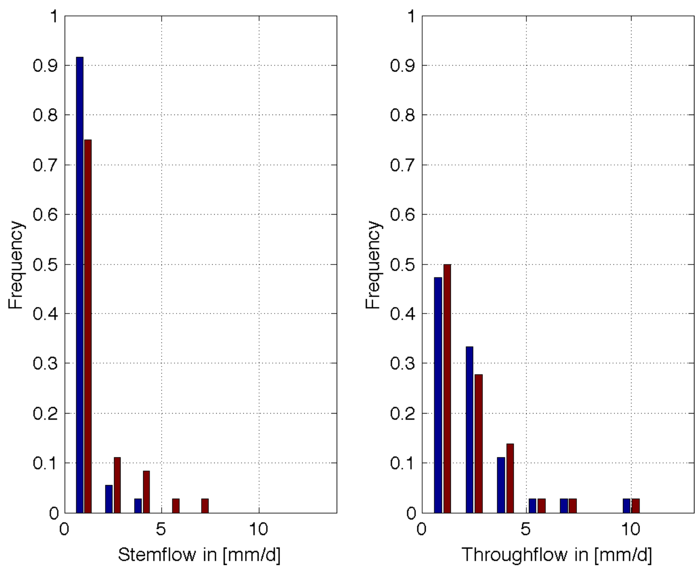


**Figure 3.4.** Histogram of stemflow (left) and throughfall (right) intensities in millimeter per day for *Leucaenia* (red) and *Pithicellobium* (blue) tree species

Figure 3.4 shows the histograms of stemflow and throughfall separately for both species. Also, small events are more frequent than larger events. While the histograms of throughfall are similar for both species, stemflow histograms differ: *Pithicellobium* (blue) only yields stemflow up to 4mm/d, while *Leucaenia* (red) may deliver fluxes up to 7.5 mm/d.

This is although both species were subject to the same events, and it highlights once more the increased delivery of stemflow by *Leucaenia*.

Figure 3.5 shows the time stability plots for both stemflow and throughfall. The normalized throughfall for individual collectors is given for the monsoon season 2010 for 65 collectors and 21 events. Similar for stemflow time stability was plotted over 36 periods for 26 locations (stemflow gauge) in two seasons 2008 and 2009, Figure 3.5 (bottom). The size of the boxes indicates the temporal variation at the observed spot (x-axis). For example in Figure 3.5 (bottom), stemflow collector number 1 always collects below average fluxes, since the box is located below the line where $\delta_{TF}$=0. The plots imply temporal stability for both throughfall and stemflow, with some spots persistently contributing below or above average fluxes. We do not observe much difference in the patterns of throughfall and stemflow. In both plots, about one third of the observed gauges has a tendency to collect above average, one third a tendency to collect below average and one third a tendency to collect average fluxes.

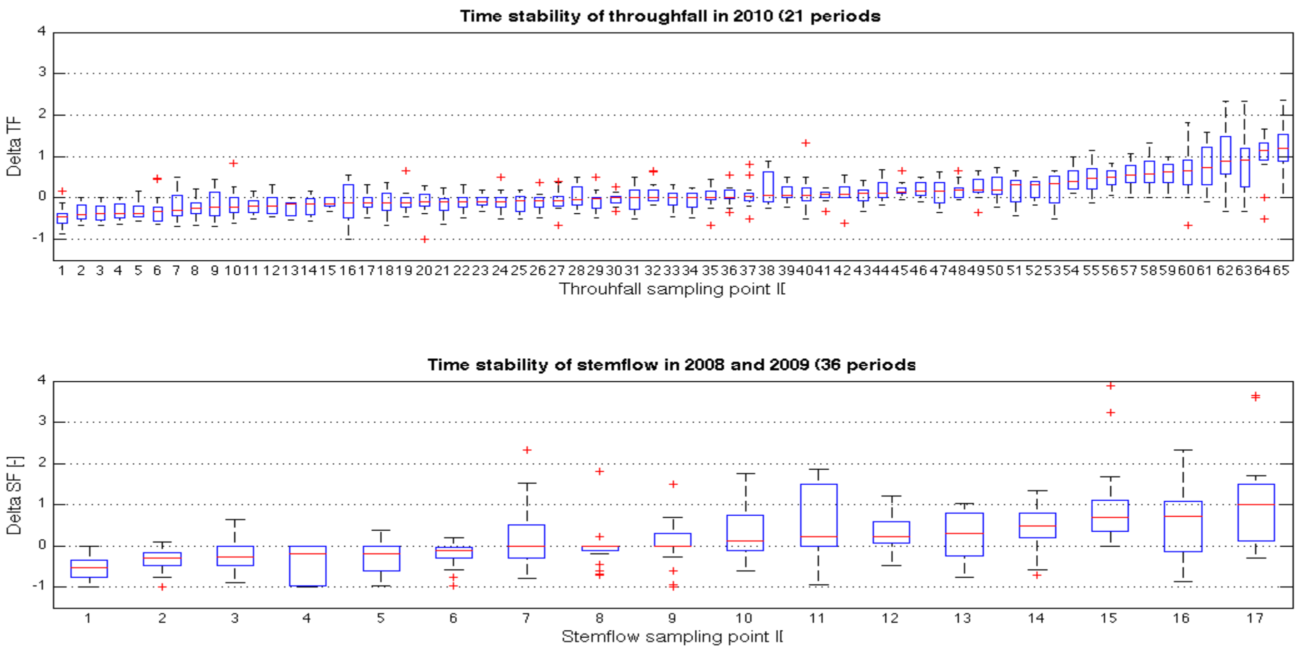


**Figure 3.5.** Time stability plots for throughfall in 2010 season for 21 periods (above) and time stability plots for stemflow in 2008 & 2009 seasons for 36 periods (below), the red line is the median of the period, lower and upper lines are minimum and maximum of event.

The same values used for assessment of time stability ($\delta_{TF,i}$) can be used to test, if spatial variation relates to canopy properties. This is visualized in Figure 3.6. The canopy cover above the throughfall collectors was classified into four classes from canopy gap (no cover) to dense cover (three and more canopy layers). The relative difference between the individual location and the overall event median was calculated and plotted separately for small event medians ( $P_{TF} < 9$ mm/d, n=16) and large event medians ( $P_{TF} > 9$ mm/d, n=5). Although much fewer events are of the larger size (only 5) they contribute more water (69 mm) than the greater number (n=16) of smaller events, which contribute together only 40 mm of throughfall. For small events, no influence of canopy cover on the spatial variation of throughfall is evident ($r^2$=0.04), except that smaller than average fluxes occur consistently in canopy gaps. However, in larger events there is a relation between the spatial variation of throughfall and the canopy cover: More water is collected with increasing canopy density ($r^2$=0.22).

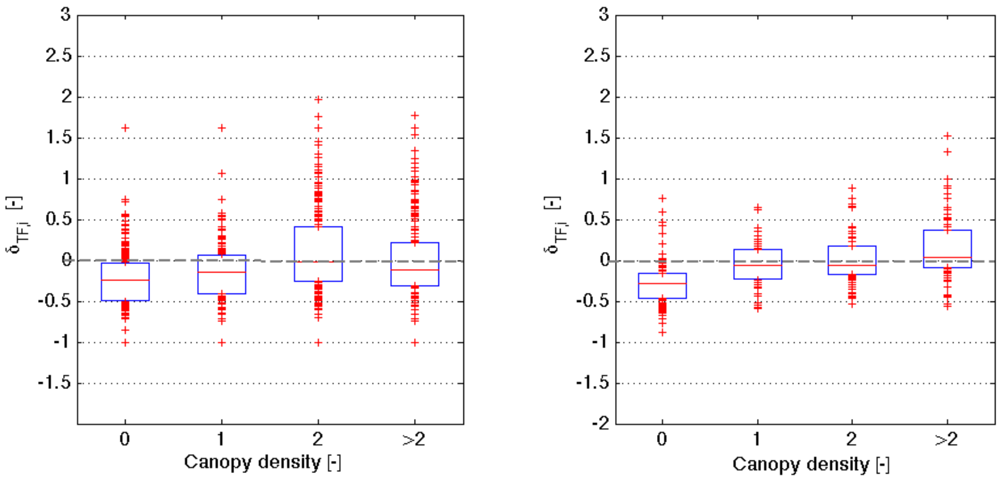


**Figure 3.6.** Relative difference of individual throughfall collection and event median compared with canopy density, left for small events ($P_{TF}$<9 mm/d, n=16) and right for larger events ($P_{TF}$ > 9 mm/d, n=5). Canopy density = 0 refers to canopy gaps.

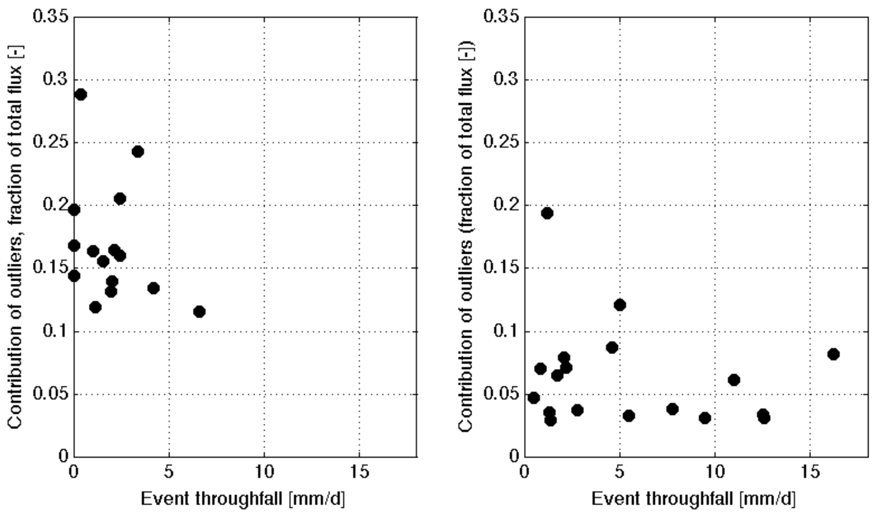


**Figure 3.7.** Relative contribution of sample outliers to the total collected stemflow (left) and relative contribution of dripping points to total received throughfall (right)

Next, we are interested not only in the temporal persistence of spatial heterogeneity, but in particular on the temporal stability of extreme points of below canopy water flow. For this we calculated the outliers of each sampling day for both stemflow and throughfall using the Grubbs Test (Grubbs, 1969). Outliers contribute substantial amounts of water to the average below canopy fluxes, as Figure 3.7 shows: For stemflow, outlier points contribute more than 10% and for small events up to 30% to the mean of stemflow. For throughfall the contribution is up to 10% and for small events up to 20%. Thus, outliers have the capacity to yield substantial elevated below canopy precipitation intensities.

Outliers occurred almost at every second sampled stemflow event (p=0.44) and much more frequently (p=0.84) in throughfall events, figure 3.8. In both cases outliers were limited to few locations: About 14% of the sampled locations were potential outlier locations. However, in stemflow, one individual tree was much more likely to serve as an outlier compared to the others (it covered 82 % of the periods when an outlier was observed at all). In throughfall, outlier points were more “mobile”, the most frequently sampled point was only observed as an outlier in 33% of the periods. In addition, the probability of a point defined as an outlier once event will become an outlier again for both throughfall and stemflow are 1 and 0.67, with a high probability that the outlier will return the following day. This shows that outliers in both throughfall and stemflow have a comparatively strong persistence and have a potential to serve as hotspots of infiltration.

Also, dripping points had a tendency to occur in denser canopy (55% of the dripping points occurred with density larger than 2 canopy layers, although only 38% of the collectors were located there).

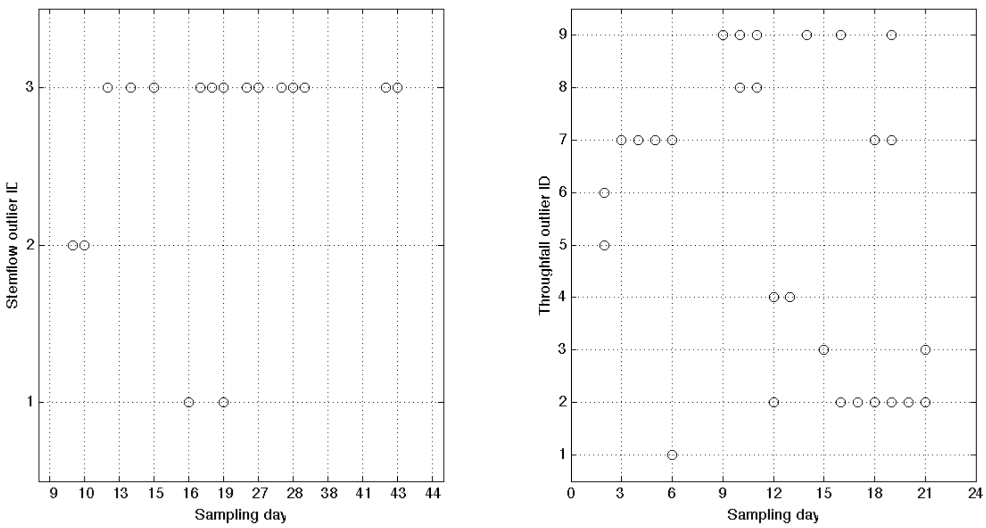


**Figure 3.8.** Active dripping point for throughfall (right) and outliers in stemflow (left) for each sampling day.

## 3.3 Discussion

Water in semi arid environment is important. Water reaches the soil surface under canopy as throughfall and stemflow is proportional to rainfall. The canopy modifies the precipitation and the water arriving at the soil underneath canopies. The canopy passage leads to heterogeneous spatial distribution. Throughfall dripping points and stemflow points play a great role for cumulative water flux in certain places. The nature of precipitation in Dhofar is characterized as drizzle. Figure 3.1 shows that most of rainfall event sizes are less than 6 mm per day. Although, throughfall in this site is greater than rainfall, the amount of throughfall water is proportional to the rate of rainfall. The frequencies of event average throughfall are comparable to those of rainfall. However, the passage of the rain through the canopy creates heterogeneity and leads to much increased intensities of below canopy fluxes.

At the level of small throughfall event we do not see an influence of the canopy cover, whereas as at intermediate throughfall events ($9 < P_{TF} < 10$ mm/d) throughfall increases and shows a dependence on the canopy. The increase of throughfall with canopy density is probably the most direct proof of cloud capture in this forest. As a side effect the dependency on canopy cover could also be a result of overloading of stemflow path. It is well known that the increase in rainfall leads to decrease in stemflow and increase in throughfall due to creation of dripping points (Crockford and Richardson, 2000). However, since the contribution of dripping points to the overall throughfall decreases with event size, we believe that this is not the dominant factor for explaining the increased throughfall with canopy density. This implies that denser canopy leads to wetter soil beneath, while in places without canopy cover the soil receives less water. Investigation in spruce forest showed that heterogeneous water distributions under canopies are due to three reasons (Berier et al., 1993; Whelan and Anderson, 1996). These factors are (i) heterogeneity of rain drop distribution because of turbulence above and within canopies, (ii) translocation of water within the canopy, and (iii) interception loss differences, which are related to canopy density. In this investigation the heterogeneity of rainfall distribution in throughfall variability was presumed to be negligible due to the small size of the plot (11m X 7m). On the other hand, the difference in cloud interception from the canopy is elevated with an increase of collecting bodies. Thus, canopy cover might have affected throughfall spatial distribution in our site.

The canopy cover creates spots, which receive much more water than other areas below the canopy. However, some points deliver especially elevated fluxes, due to peculiarities in the branches and movement of leaves and small branches. These dripping points are outliers. Outliers occur frequently for both stemflow and throughfall, but more persistently at the same spot for stemflow. This might be a result of the geometry of the individual tree or particularly conducting bark. In general, we expect that stemflow is the most efficient pathway for water towards the soil, since it strongly enhances flux intensities by funneling water from a larger area towards a small spot. It is also persistent in time, and probably allows for longer lasting soil moisture patterns in the soil, compared to outliers of throughfall.

## 3.4 Conclusion

Spatial pattern of throughfall and stemflow in the semi arid cloud forest varied over time and space. Canopy passage increased the heterogeneity of the water arriving at the soil and leads to enhanced fluxes, which show some time stability. Cloud capture was evident through the relation between throughfall and canopy density, and suggests that infiltration rates below canopies are larger than in gaps in this environment. Hotspots (outliers) of stemflow contributed a large fraction of the average stemflow and occurred most frequently at the same spot. The study suggests that stemflow could provide larger water availability at the soil surface compared to throughfall.

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# Chapter IV

# Lag Time Estimation of Stemflow and Throughfall in Semi Arid Cloud Forest, Dhofar

Initially the rainfall wets the canopy surface. There is a lag time between the onset of rainfall or fog events and stemflow and throughfall. Theoretically stemflow and throughfall occur after water input events (rainfall or fog) under the condition that the canopy is dry. However, this ideal condition is difficult to satisfy in a cloud forest due to the presence of fog. In other words, the canopy has a certain degree of wetness, although the rainfall events stop.
In cloud forest tree canopies direct input water, which precipitate in the form of rainfall or fog (Lelong et al., 1990; Roda et al., 1990), is redistributed. The input water reaches the forest floor after canopy storage capacity and stem storage capacity are saturated (Leyton et al., 1967; Yusop et al., 2003). The time between the input events and events of net precipitation components (throughfall and stemflow) is referred to as lag time. The lag time differs for throughfall and stemflow depending on many factors such as the canopy properties and stem types (Crockford and Richardson, 2000). Area of leaves and their orientation influence the droplets of fog and drizzle. Moreover, the smoothness of the stem and vertical angles of branches channel water faster toward the forest floor (Levia et al., 2010). However, it is a known fact that rainfall and fog events occur first, and throughfall and stemflow occur later.
So it is desirable to know which parameters start and end earlier. In addition, for which tree species throughfall and stemflow acts faster, and which parameter (stemflow, throughfall) has a longer duration within each event.

We hypothesis that no difference in stemflow between species *Leucaenia leucacephala* (B) and species *Pithicellobium dulce* (A), specially, we know throughfall for both species is equal. Using high resolution data to test if the storage capacity of tree species is the reason for stemflow of B greater than A or simply that B collects more water than A due to its efficiency to drainage water more. Thus, relate the storage capacity to the lag time of throughfall and stemflow

The aim of the this section is to investigate the lag time between rainfall or fog events and the throughfall and stemflow events for two tree species (*Leucaenia leucacephala and Pithicellobium dulce*) located in the interior of the semi arid cloud forest. In addition, we provide an estimate of the storage capacity for both tree species.

## 4.1 Materials and Methods

### *4.1.1 Site Description*

The field study was conducted in the Dhofar region of Oman. Details of the site and area climate and hydrology are mentioned in chapter II (Bawain et al., submitted).

Vegetation cover in the coastal plains consists of grass and shrubs and tree vegetation mostly occurs in the mountains. Due to livestock pressure, grass is the dominating vegetation in mountain regions accessible for pastoral land use. However, steep slopes along the intermittent river courses (locally called *wadis*), inaccessible for the majority of livestock, show the natural tree vegetation of the mountains.

Measurements were conducted at the Tawi Attair forest enclosure (Bawain et al., submitted). Data for throughfall, stemflow, fog, rainfall, as well as basic climatic parameters were collected within an experiment site at the southeast corner of the enclosure, Fig.4.1. The experiment site occupied a total area of 7000 $m^2$.

Within the experiment site, two plots situated in the internal area of the forest of two different tree species were delineated and surveyed; *Pithicellobium dulce* trees and *Leucaenia leucacephala* trees.

For simplicity, we refer to species *Pithicellobium dulce* as A and species *Leucaenia leucacephala* as B. Climatic parameters can be assumed equal, because the size of the plots is near each other and the size is small. In addition, soil texture throughout the experimental site is characterized as clayey (survey data not shown) with a homogenous distribution (chapter II; Bawain et al., submitted). Data were collected automatically by tipping buckets for the 2010 monsoon season.

**Fig.4.1.** Photograph of Tawi Attair enclosure *(Taken by Abdullah Bawain).*

### *4.1.2 Measurements/Instruments*

Plots in year 2010 are equipped with automatic loggers. In the two experiment plots throughfall buckets and stemflow gauges were installed, Table 4.1 shows the number of measurements in each plot.

#### *4.1.2.1 Throughfall*

Gutters are used in season 2010 for throughfall measurement. Three PVC pipes cut longitudinally are positioned under the tree canopy, in which one end is positioned at tipping bucket funnel and other end is hung between trees branches. The sitting of pipes for throughfall is illustrated Fig. 4.2. The aim of using pipes is to cover as much area under tree canopy as possible. The area of collector (pipes) and tipping volume for each plot are corrected (Equations 4.1, 4.2 & 4.3). The details of pipes are illustrated in Table 4.2. Throughfall readings were converted to millimeter per day.

**Fig.4.2.** Photograph of throughfall collection apparatus under a *Leucaenia leucacephala* tree (Plot B). Cross sectional of throughfall gutter (left bottom). Pipes drain to the tipping-bucket gage *(Taken by Abdullah Bawain).*

In total 6 gutters (collectors) linked to tipping buckets were used to sample throughfall automatically. Collectors varied in length, angle of decline and height from the ground. Thus the length of each gutter is corrected, Equation 4.1. Then, the collection area is calculated as the sum of areas of all three gutters plus the area of the tipping bucket funnel, Equations 4.1, 4.2 and 4.3. Throughfall readings were converted to millimeter per day.

$$l_{corrected} = \sqrt{a^2 - (c-h)^2} \tag{4.1}$$

$$A_{Pipe} = D_{Pipe} * l_{corrected} \tag{4.2}$$

$$A_{Total} = A_{Pipe} + A_{Funnel} \tag{4.3}$$

Where $l_{corrected}$ is the pipe length in (m), $a$ is the actual pipe length in (m), c is the height of pipe end from ground to tree branch in (m) and $h$ is the height of the lowest pipe end from ground to funnel edge in (m), $A_{Pipe}$ is the pipe area in ($m^2$), $D_{Pipe}$ is pipe diameter in (m), $A_{Total}$ is the surface collecting area in ($m^2$) and $A_{Funnel}$ is funnel area ($m^2$).

Table 4.2 illustrates the throughfall collector's properties for both plots. Because pipes used in throughfall measurement were not set horizontally, the length for each pipe length must be corrected. In addition, the volume of tipping bucket must be correct due to the change in the area.

**Table 4.2.** Throughfall collectors properties and areas correction used in season 2010 measurements.

| Plot | Pipe number | Pipe length (m) | Height of funnel from ground (m) | Pipe diameter (m) | Height of pipe from ground (m) | Correction pipe length (m) | Pipe area ($m^2$) | Total area of pipes ($m^2$) | Funnel area ($m^2$) | Total area ($m^2$) | New Tipping Volume (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $A_{Int.}$ | Pipe1 | 3.7 | 0.67 | 0.054 | 1.78 | 3.52 | 0.19 | 0.69 | 0.03 | 0.72 | 0.0113 |
| | Pipe2 | 3.5 | | | 1.20 | 3.46 | 0.19 | | | | |
| | Pipe3 | 6.0 | | | 2.28 | 5.78 | 0.31 | | | | |
| $B_{Int.}$ | Pipe1 | 6.0 | 0.86 | | 3.98 | 5.13 | 0.28 | 0.76 | 0.04 | 0.80 | 0.0098 |
| | Pipe2 | 6.0 | | | 2.14 | 5.86 | 0.32 | | | | |
| | Pipe3 | 3.4 | | | 2.19 | 3.10 | 0.17 | | | | |

#### 4.1.2.2 Stemflow

Stemflow was sampled at altogether 10 stems from two tree species, at the two plots. Strips of 3-inch flexible plastic hoses were wrapped around the stems and fixed using super glue. At the lowest point, a pipe of 10 mm diameter was inserted and connected to automatic tipping bucket gauges. Silicone sealant was used to seal the gaps between the stem and the tube strip (Hildebrandt et al., 2007). Table 4.1 gives an overview of the number of stemflow gauges in each plot. Collected stemflow volume was transferred to a flux per square meter (comparable to precipitation rate) using the following method. Within each plot, all tree stems were counted, and the following equation was used to calculate stemflow ($P_{SF}$ in mm $d^{-1}$):

$$P_{SF} = \left(\frac{V_{SF}}{n_{obs}}\right) * \left(\frac{n_{tot}}{A_P}\right) * \left(\frac{1}{t}\right) \tag{4.4}$$

Where $P_{SF}$ is the stemflow in (mm $d^{-1}$), $V_{SF}$ is the total stemflow volume (in l) collected at all gauges in this plot since the last visit, $n_{obs}$ is number of stems with stemflow gauges (-), $n_{tot}$ is total number of stems within this plot (-), $A_P$ is the plot area in ($m^2$) and $t$ is the time interval between two consecutive measurements in (d).

**Table 4.1.** Equipment and plot properties.

| Parameter | Plot | |
|---|---|---|
| | $A_{Int.}$ | $B_{Int.}$ |
| Area ($m^2$) | 191 | 136 |
| # Stem (-) | 26 | 25 |
| Tree Height Average (m) | 6.4 | 9.3 |
| Tree species | *Pithicellobium dulce* | *Leucaenia leucacephala* |
| Throughfall | 1 | 1 |
| Stemflow | 5 | 5 |
| Rain _ Tower | 1 | |
| Rain_ Ground | 1 | |
| Fog | 1 | |
| Basic climate station | 1 | |

* Throughfall has 3 pipes drain to the tipping bucket for both plots

#### *4.1.2.3 Fog*

The fog collector used in this experiment was adapted from a Fischer and Still (2007) design. The collector was made at the UFZ workshop, Leipzig, Germany. Two pairs of stainless steel threaded rods were inserted horizontally in a cross shape into PVC pipe of 2.7 cm diameter at a 60 cm distance from each other. An aluminum shield of 0.5m radius fixed on the top used to prevent incident rain from disturbing the measurement process (David McJannet et al, 2007). Monofilament fish line of 0.72 mm diameter was stretched vertically between threaded rods. The spaces between the vertical stretches were kept at 9 mm. Two half tubes of 0.5 inch diameter were fixed beneath the bottom rods to collect the water from the vertical stretches. At the center of the tubes, holes were drilled to allow the water to drain through a pipe of 10mm diameter to the tipping bucket positioned on the ground. The fog collector was mounted at a height of 7 m at the tower, Fig. 4.3.

**Fig.4.3.** Photograph of fog collector mounted at tower *(Taken by Abdullah Bawain).*

#### 4.1.2.4 Rainfall

Gross rainfall was measured by using two tipping buckets. One tipping bucket mounted 7 meters at the tower of 200 $cm^2$ funnel area. One tipping bucket on the ground mounted 1m above the ground surface of 400 $cm^2$ funnel area in an open wind shaded area at the south-west of the site (see chapter II, Fig. 2.1b).

#### 4.1.2.5 Precipitation components

Net precipitation ($P_{Net}$ in mm $d^{-1}$), the total water received below tree canopies was calculated from throughfall and stemflow as follows:

$$P_{Net} = P_{TF} + P_{SF} \tag{4.5}$$

Where $P_{TF}$ (in mm $d^{-1}$) is the measured throughfall and $P_{SF}$ (in mm $d^{-1}$) is the measured stemflow. Apparent interception ($I_a$ mm $d^{-1}$) is an estimate of the amount of water, which is either lost or gained by canopy processes. It was calculated from the observed water fluxes above (rainfall) and below (net precipitation) the canopy (adapted from Bruijnzeel et al. (2001)):

$$I_a = P_{Rain} - P_{Net} \tag{4.6}$$

Where, $P_{Rain}$ is the rainfall (mm $d^{-1}$). Negative apparent interception indicates cloud capture or horizontal precipitation. Cloud capture might still be present when apparent interception is positive, but in this case, evaporation loss from the moist canopy was larger than cloud capture. Taking in account that if $I_a \geq 0$, it is a good predictor for gaining additional water from cloud in terms of horizontal precipitation during that event. Moreover, horizontal precipitation still exists in case $I_a \leq 0$, but we ware not able to quantify it.

### *4.1.3 Analysis methods*

#### *4.1.3.1 Selection of events*

We indicate the start time and end time for each gauge. The start time means the time that a logger responds for the first time and end time refers to the last time the logger responds during a certain period. These two times are determined for rainfall, fog, throughfall and stemflow based on the following rule. In order to determine precisely the dry and wet periods for 2010 season, we took the rainfall data as an indicator. We indexed rainfall records greater than zero ($R$>0) by one (1), while no rain is coded as zero (0). The purpose of this test is to determine the beginning and the end of the rainfall events. At each index point equal to one (index=1), time of two hours are subtracted from the index point time to identify the start of rain ($S_R$) and two hours are added to time of the index point to specify the end of rain ($E_R$).
In case the sum backward from index point is zero (0), this is the start of the rain event. In addition, the end is determined in the same manner, but in the forward direction from the index point. The procedure is applied for all index points. A similar rule is applied for stemflow gauges, throughfall gauges and fog gauge, to identify their start and end events ($S_{st}$, $E_{ST}$, $S_{th}$, $E_{th}$, $S_f$, *and* $E_f$), fig.4.4.

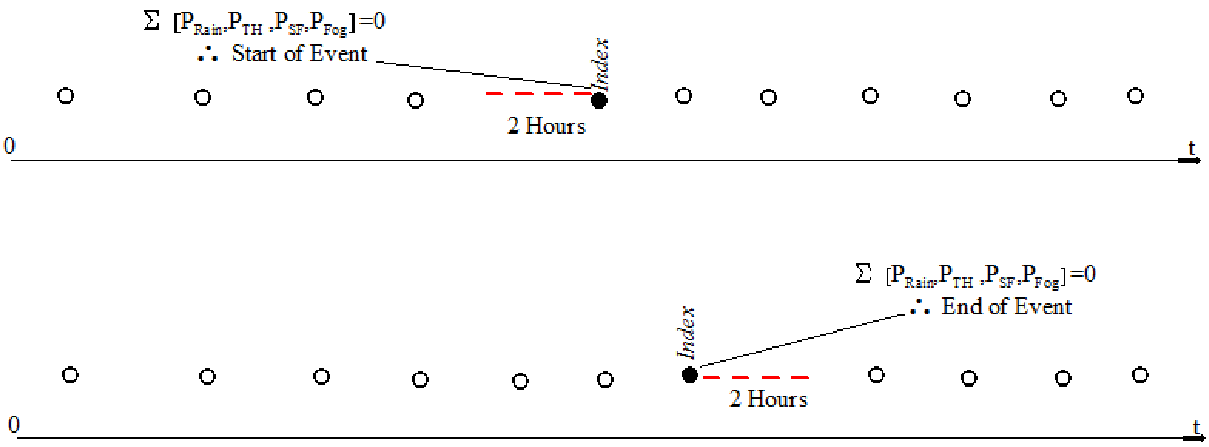


**Fig.4.4**. schematic to identify start (top) and end (bottom) of rainfall, fog, stemflow and throughfall events

From this step we have 68 events for fog, 66 events for rain, 75 events throughfall of plot A and 84 events for throughfall B. In addition, plots have five (5) stemflow gauges each, thus gauges do not have same event even within the same plot. The maximum number of events found for plot A is 41 and for plot B 37 events, after determining the start and end events for each sensor (gauge) separately. The event for all measurements needs to be specified. An event refers to the period of time between the starts and ends of all gauges following a water input, either rain or fog. The start of the event ($S_{En}$) is determined by subtracting one hour from the beginning of each rain event ($S_R$).

$$S_{En} = S_R - 1h \tag{7}$$

It is assumed no throughfall or stemflow will be generated without the start of rain or fog and will not stop without the stop of both rain and fog. Thus, we first limit the gauge events located within each rainfall event (66 events). We plotted the start and end bar for each gauge within a single rainfall event. Then, we checked for gauges (fog, throughfall and stemflow) that start and end before and after the rainfall events (start/end). Second, we indicated the start time of the event as the time of the first gauge response in the event and the end as the last time a gauge reacts.

We investigate within each fog, throughfall and stemflow events which one is continuous. We look for a continuous gauge and modify the start and the end to those event boundaries. For example, we have two fog events locate within one stemflow or throughfall event or the way around. Then, we consider this is one event, especially as throughfall or stemflow gauges were functional.

Finally, we made manual correction to the events and checked from the start and the end of the each event for two hours (2 hr) backwards and forwards. If there was a record by any gauge before or after the signed start and end, we shifted the start or the end to that time depending on the location of this record.

After the start and end time for season events indicated, we created a master table (not shown) to calculate several parameters, such as the lag time for stemflow and throughfall, after the start of the first rain or fog and the end lag time after the stop of rain or fog, and the duration of stemflow and throughfall. The software R was used for the statistical analysis (R Development Core Team, 2008).

#### 4.1.3.2 Calculation of lag time and duration for throughfall and stemflow

Lag start time for stemflow and throughfall are calculated by subtracting the start time of throughfall from the first time of rain or fog depending on which one starts earlier. Moreover, the lag end time is computed by subtracting the latest rainfall or fog, whichever stops later. The following equations show the operation in more details.

$$Lag\_S_{T_{TH}} = S_{T_{R||F}} - S_{T_{TH}} \tag{4.8}$$

$$Lag\_S_{T_{ST}} = S_{T_{R||F}} - S_{T_{ST}} \tag{4.9}$$

Where $Lag\_S_{T_{TH}}$ is the lag start time of throughfall (hr), $S_{T_{R||F}}$ is the start time of rain or fog which start first (hr), $S_{T_{TH}}$ is the start time of throughfall event (hr), $Lag\_S_{T_{ST}}$ is the lag start time of stemflow (hr), $S_{T_{ST}}$ is the start time of stemflow (hr).

$$Lag\_E_{T_{TH}} = E_{T_{R||F}} - E_{T_{TH}} \tag{4.10}$$

$$Lag\_E_{T_{ST}} = E_{T_{R||F}} - E_{T_{ST}} \tag{4.11}$$

Where $Lag\_E_{T_{TH}}$ is the lag end time of throughfall (hr), $E_{T_{R||F}}$ is the end time of rain or fog which ends later (hr), $E_{T_{TH}}$ is the end time of throughfall event (hr), $Lag\_E_{T_{ST}}$ is the lag end time of stemflow, $E_{T_{ST}}$ is the end time of stemflow (hr).

The duration of throughfall and stemflow is the difference between the end times of last gauge minus the earliest time for the gauge and express in hours. Similar method is use for calculate the duration of stemflow in both plots.

$$D_{T_{TH}} = E_{T_{TH}} - S_{T_{TH}} \tag{4.12}$$

$$D_{T_{ST}} = E_{T_{ST}} - S_{T_{ST}} \tag{4.13}$$

Where as, $D_{T_{TH}}$ is the duration of throughfall (hr), $E_{T_{TH}}$ is the end time of throughfall (hr), $S_{T_{TH}}$ is the start time of throughfall (hr), $D_{T_{ST}}$ is the duration of stemflow (hr), $E_{T_{ST}}$ is the end time of stemflow (hr) and $S_{T_{ST}}$ is the start time of stemflow (hr).

#### *4.1.3.3 Selection of working events*

We assume that low net precipitation events are subject to high error, thus we use net precipitation of 1.0 mm per day as a critical value to select events to do the calculation. Out of 50 events of the season of 2010, 26 events are greater than 1.0 mm per day for both plot A and plot B. These 26 events contribute 95% of the total seasonal amount of rainfall.

## 4.2 Results

### *4.2.1 Rainfall and Net precipitation*

Table 4.3 summarizes the precipitation budget in 2010 at Tawi Attair site for two plots of different tree species. The plots are located in the interior of the forest. The table shows species B net precipitation exceeding the gross precipitation, which points to this type of tree, having the ability to capture more rainfall and fog droplets during the monsoon or channel it more effectively to the ground. In addition, the stemflow is the essential factor in net precipitation components. The majority of the events show that stemflow volumes for B are approximately double stemflow volumes for species A ($P_{SF\_B}=2*P_{ST\_A}$). On the other hand, throughfall is approximately equal for both species, see Fig.4.5 & 4.6.

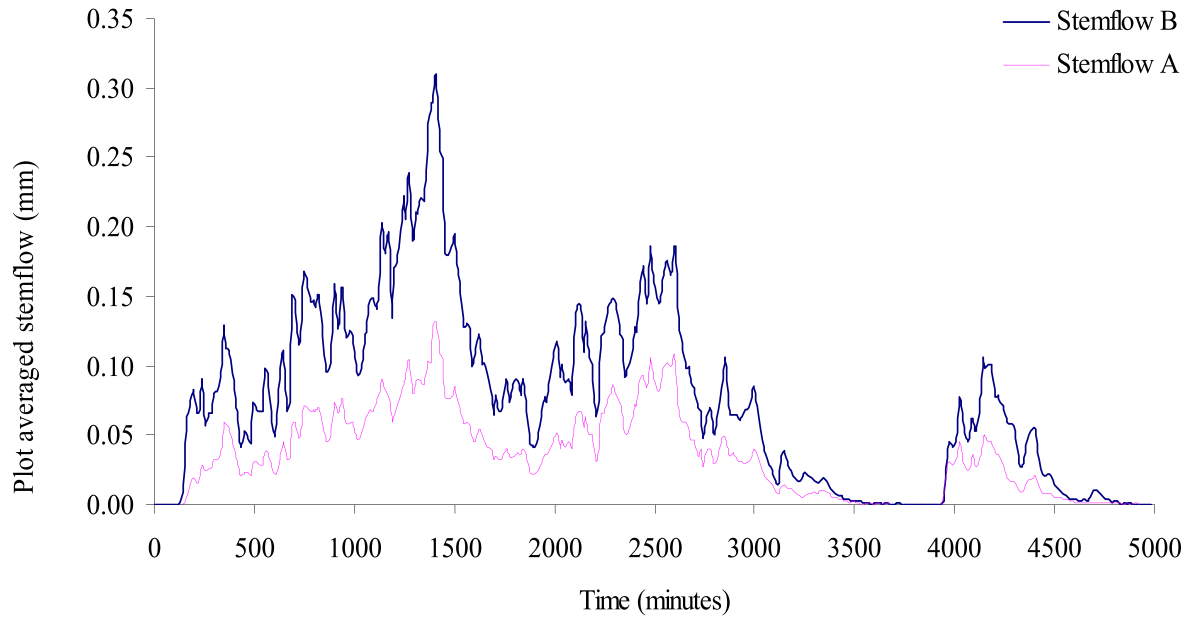


**Fig.4. 5.** Temporal variation in the stemflow yield of *Leucaenia leucacephala (B)* & *Pithicellobium dulce* trees at 15 min intervals during the 21-24 August 2010 rain events (40.2 mm).

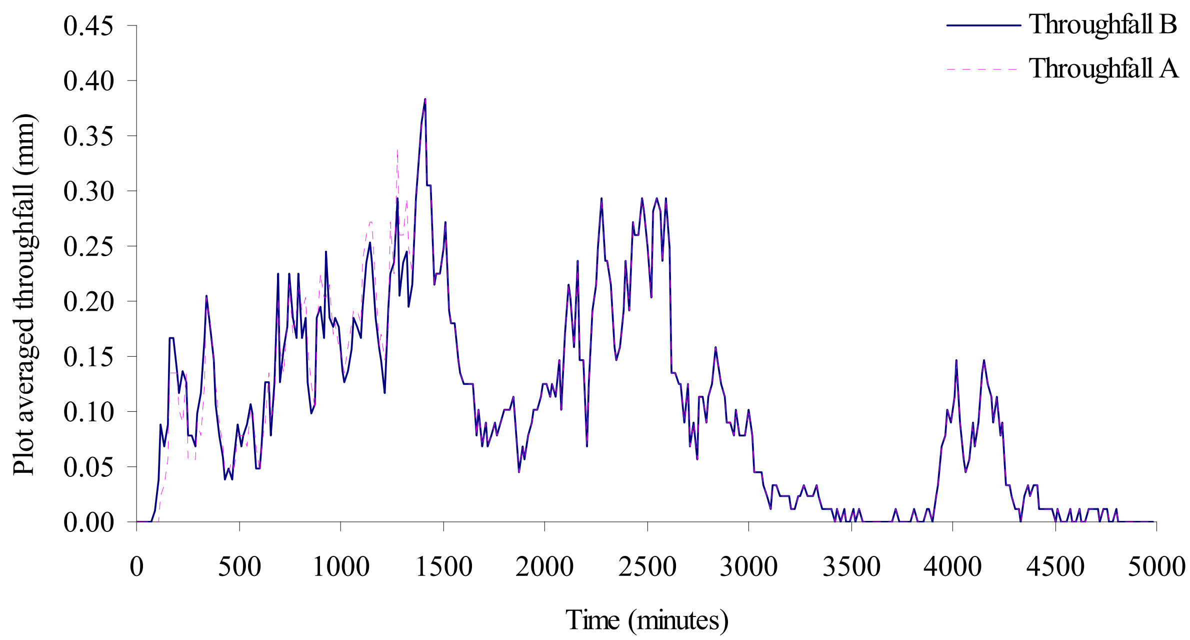


**Fig.4.6.** Temporal variation in the throughfall yield of *Leucaenia leucacephala (B)* & *Pithicellobium dulce* trees at 15-min intervals during the 21-24 August 2010 rain events (40.2 mm).

**Table 4.3.** Summary of precipitation budget season 2010.

| Plot | Tree species | Stat. parameters | Number of Events | Event length [hr] | Rain [mm] | Fog [l] | $P_{SF}$ [mm] | $P_{TF}$ [mm] | $P_{Net}$ [mm] | $P_{TF}/P_{Net}$ | $P_{SF}/P_{Net}$ | $P_{Net}/P_{Rain}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $A_{Int.}$ | *Pithicellobium dulce* | Total | 26 | 809.8 | 199.0 | 30.2 | 50.5 | 140.3 | 190.8 | 0.74 | 0.26 | 0.96 |
| | | Max | | 101.0 | 43.0 | 4.7 | 12.3 | 34.7 | 47.1 | | | |
| | | Min | | 3.0 | 0.4 | 0.0 | 0.0 | 0.3 | 0.3 | | | |
| | | Average | | 31.1 | 7.7 | 1.2 | 1.9 | 5.4 | 7.3 | | | |
| | | SD | | 26.94 | 10.12 | 1.26 | 2.69 | 7.61 | 10.25 | | | |
| $B_{Int.}$ | *Leucaenia leucacephala* | Total | 26 | 809.8 | 199.0 | 30.2 | 109.0 | 128.3 | 237.3 | 0.54 | 0.46 | 1.19 |
| | | Max | | 101.0 | 43.0 | 4.7 | 26.3 | 20.7 | 39.4 | | | |
| | | Min | | 3.0 | 0.4 | 0.0 | 0.0 | 0.3 | 0.3 | | | |
| | | Average | | 31.1 | 7.7 | 1.2 | 4.2 | 4.9 | 9.1 | | | |
| | | SD | | 26.94 | 10.12 | 1.26 | 5.71 | 5.38 | 10.51 | | | |

After filtering the events, we ended up with 26 events; those having a net precipitation greater than 1.0 mm/day. These events express 95% of rainfall of the season's gross precipitation. Figure 4.7 shows the rainfall intensity for season 2010 ranging from 0.08 to 0.23 mm/hr.

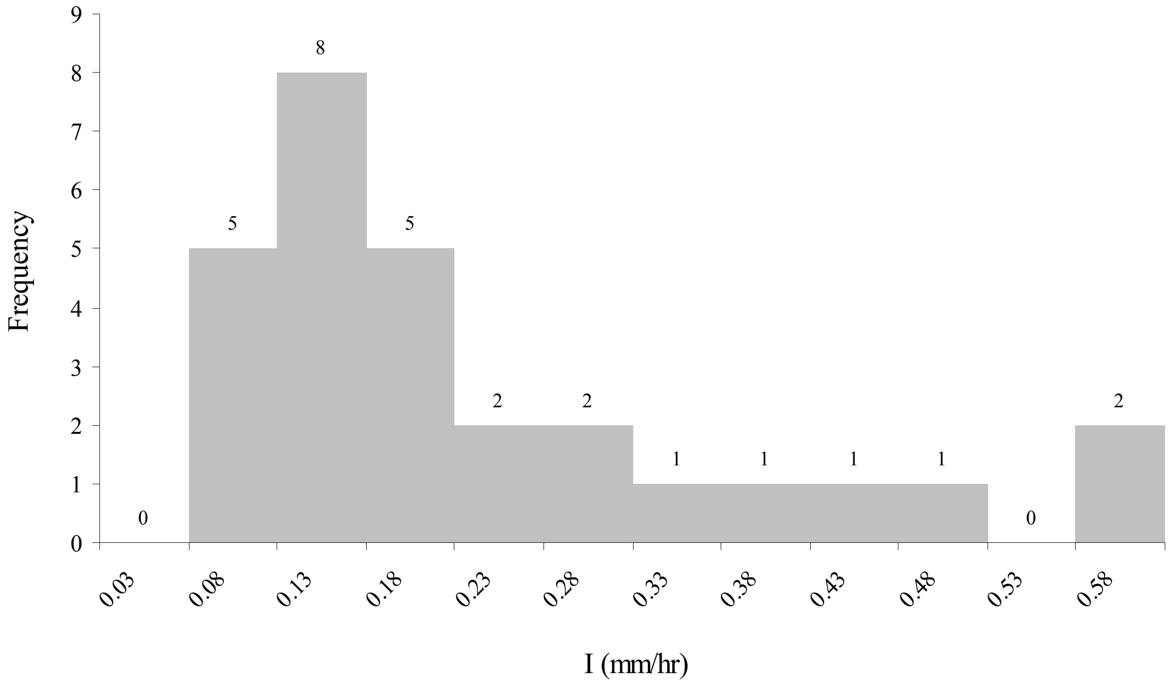


**Fig.4.7**. Histogram of selected events of rainfall intensity for season 2010

Figure 4.8 illustrate the precipitation budget for season 2010 sorted by rain. The figure consists of fog, stem-ratio and time difference to previous event (delta). The stem-ratio refers to the division of stemflow for species B by stemflow for species A. The figure describes the cloud forest budget of semi arid environment site at Tawi Attair. It shows net precipitation (stemflow and throughfall) associates with the magnitude of rainfall. However, fog input plays role in the net precipitation and the effect is significant clear in event number 15. In other words, the more fog water, the more net precipitation. The last part (interception) of the figure is a good indicator for which type of tree species collect or loose water. It is clear species B gains more water than species A.

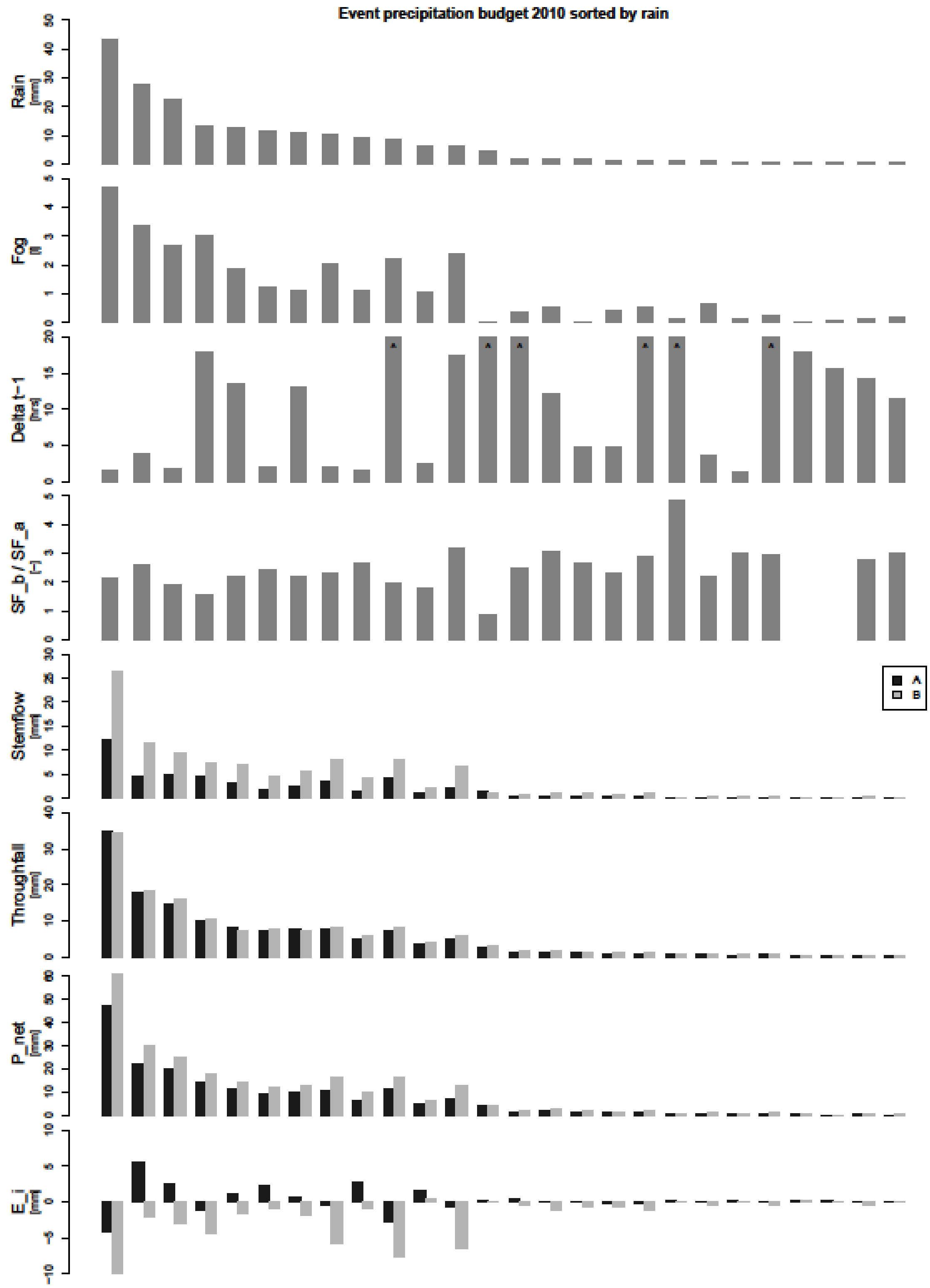


**Fig.4.8.** Event precipitation budget 2010 sorted by rain.

### 4.2.2 Lag times and duration for different precipitation components

Lag times at the event starts and event ends between stemflow and throughfall for 26 events of two tree species (A and B) are illustrated in Tables 4.4 & 4.5. Table 4.4 show the number of events of stemflow for species A and species B starting at the same time and at different times. For instance, the majority of stemflow events (16 events) start at the same time for stemflow A and stemflow B (62% from the total number of periods). In contrast, nine events ended at the same time for both species (35%). However, the majority of stemflow events for species B end later than species A, which accounts for 42% of the total number of events. Hence, many stemflow events for species take longer until they end (50%). This can summarize as:

- Stemflow for species B stops later
- Stemflow for species B has longer duration.

**Table 4.4.** Difference in stemflow events time between *Pithicellobium dulce* (A) and *Leucaenia leucacephala* (B).

| | Start of stemflow | | End of stemflow | | Duration | |
|---|---|---|---|---|---|---|
| | No. | % | No. | % | No. | % |
| + | 4 | 15% | 4 | 15% | 6 | 23% |
| - | 4 | 15% | 11 | 42% | 13 | 50% |
| = | 16 | 62% | 9 | 35% | 5 | 19% |
| na | 2 | 8% | 2 | 8% | 2 | 8% |

Data in the table is calculated on time difference of A-B. The signs mean (+) stemflow of A starts/ends later (B starts/ends earlier), (-) means stemflow of B starts/ends later (A starts/end earlier), (=) stemflow of A and stemflow of B starts/ends at the same time and (na) means measurement is not available.

Similar to the stemflow the majority of throughfall events for species A and species B start at the same time (i.e. twenty events, Table 5). However, in eleven throughfall events, throughfall of species B ends later than throughfall of species A (42%), Table 4.5. It has been noticed that:

- Throughfall within each plots starts before stemflow

**Table 4.5.** Difference in throughfall events time between *Pithicellobium dulce* (A) and *Leucaenia leucacephala* (B) of throughfall.

| | Start of throughfall | | End of throughfall | | Duration | |
|---|---|---|---|---|---|---|
| | No. | % | No. | % | No. | % |
| + | 2 | 8% | 6 | 23% | 6 | 23% |
| - | 4 | 15% | 11 | 42% | 9 | 35% |
| = | 20 | 77% | 9 | 35% | 11 | 42% |

Data in the table is calculated on time difference of A-B. The signs mean (+) throughfall of A start/end later (B start/end earlier), (-) means throughfall of B starts/ends later (A starts/end earlier) and (=) throughfall of A and throughfall of B starts/ends at the same time.

### *4.2.3 Storage capacity*

Storage capacity is the amount of water that can be stored on the vegetation canopy surface and on the stem surface. Both throughfall and stemflow take place when canopy and stem surfaces are saturated. Figures 4.9 & 4.10 illustrate the relationship between gross rainfall and net precipitation components (throughfall and stemflow) for both tree species. The figures represent seasonal rainfall events for which the time difference to previous events was greater than 8 hours.

A period of 8 hours between events is assumed to be enough for the canopy to be dry prior the event. Base on the graphic method (Leyton method), the canopy storage capacity for species A is estimated at 1.0mm and for species B at 0.4mm. Theses are the interception points on throughfall axis. Similarly, the interception points on stemflow axis for species A and species B are 4.1mm and 0.1mm, which represent the stem storage capacities of the two tree species. According to the Leyton method, species A has greater storage capacities than species B.

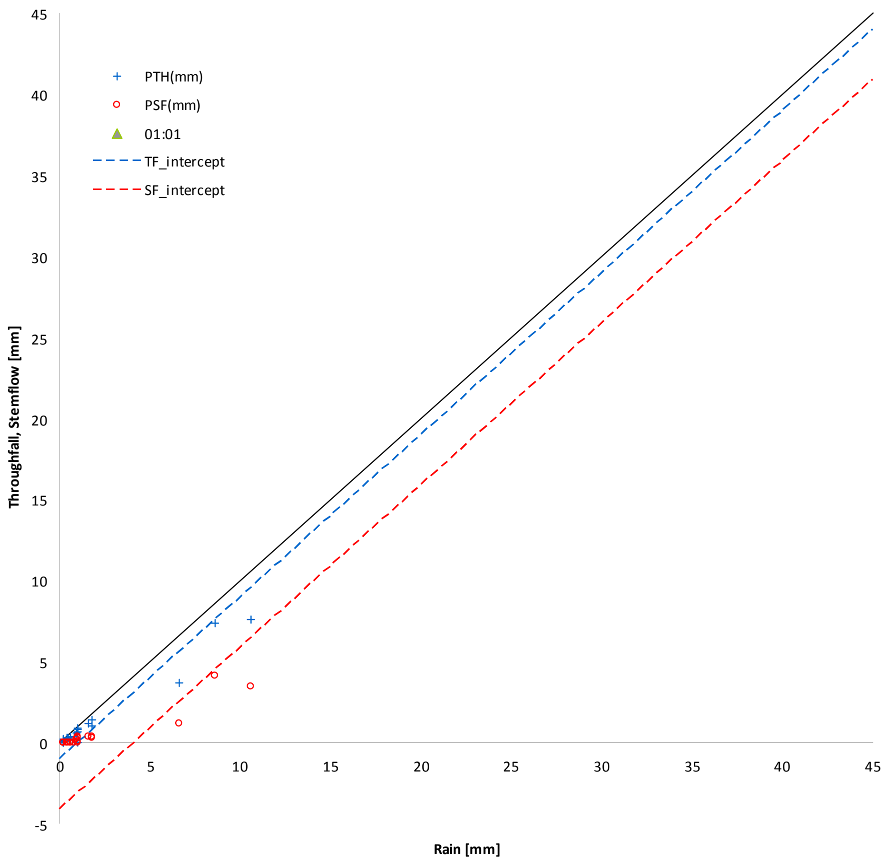


**Fig.4.9.** Seasonal rainfall events with time difference to previous events greater than 8 hours versus net precipitation components for species A (*Pithicellobium dulce*); (red circle) stemflow, (blue cross) throughfall.

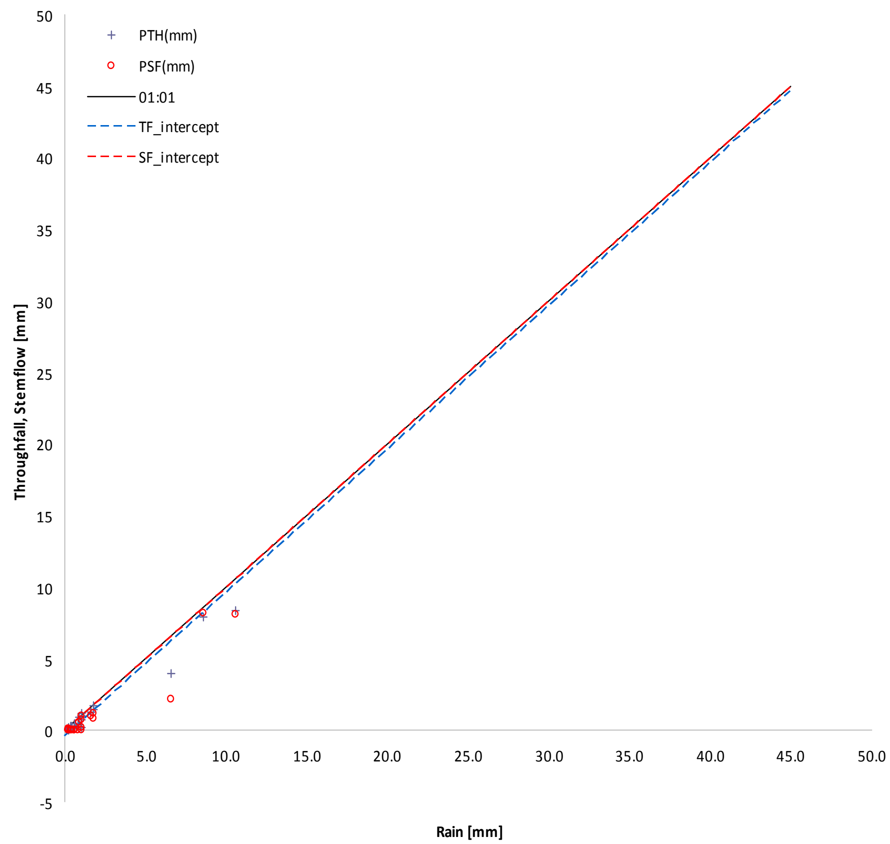


**Fig.4.10.** Seasonal rainfall events with time difference to previous events greater than 8 hours versus precipitation components for species B (*Leucaenia leucacephala*); (red circle) throughfall, (open triangle) stemflow.

## 4.3 Discussion

In this semi arid cloud forest, rainfall precipitates as drizzle. The start and the end of rainfall events are not only govern by rainfall itself, but fog plays an important role in the system.

We investigated lag times between net precipitation and water that enters the system at semi arid cloud forest. For this research we selected two plots located in the interior of the forest. Each plot consists of a single tree species. For the selected events (26 event), we calculated lag time and duration. For most events throughfall and stemflow for both tree species start at the same time, Table 4.4 & 4.5. For instance, 62% and 77% of stemflow and throughfall events start at the same time for both species. However, the majority (42%) of throughfall and stemflow events for species B end later than species A. In addition, 50% of stemflow events for species B have a longer duration than species A. Moreover, 35% of throughfall events for species B are longer than species A, table 4.4 and table 4.5. This is due to the smoothness of the bark, which allows even small amounts of water to be channeled toward the ground. But rough bark retains the water. Moreover, the tree height plays a role in collecting more water than shorter one. This is the case for species B.

For events that start after rainfall or fog input (table not shown), stemflow takes 1.4 hours on average to react after rainfall occurrence for species B; stemflow for species A starts 1.3 hours after the rainfall start. Stemflow takes for species B more time to generate and stop maybe due the height of trees and bark structure. Throughfall of species A takes on average 0.5 hours to generate; for species B throughfall starts 0.6 hours after the rain start. The time difference between two tree species is close to the measurement interval which is 15 minutes.

In terms of the precipitation budget, we can confirm our findings from 2008 & 2009 that species B (*Leucaenia leucacephala*) captures more water than species A (*Pithicellobium dulce*), this is due to the stemflow volume which amounts to 41% of net precipitation for B and 26% for A. Thus, we find stemflow of species B is greater than stemflow of species A (Chapter II; Bawain et al., submitted; Fig. 4.5). However, we also found that throughfall is approximately equal for both species (Fig. 4.6). The results for season 2010, again, emphasize the previous results (seasons 2008 and 2009) for throughfall and stemflow for both tree species, Table 4.3. The measurements from three years show that while rainfall amounts vary, the actual ratios of stemflow and throughfall to net precipitation are relatively constant.

The minimum and the maximum rainfall intensities for season 2010 (selected events) are 0.04 mm/hr and 0.55 mm/hr with an average of 0.19 mm/hr. However, 53% of events have intensity greater than 0.18 mm/hr and 18% of events have intensity less than 0.13 mm/hr. In addition, 29% of events have intensities ranging from 0.13 to 0.18 mm/hr, as is expected for drizzle condition like at our site, see Fig. 4.7.

We investigated in depth why species B intercepts more water than species A? We sorted the event precipitation budget for selected events of season 2010 by rainfall, Fig. 4.8. Comparing species B (*Leucaenia*) and species A (*Pithicellobium*) shows that, whereas throughfall is relatively similar for these species, stemflow is about twice as large for B than A. As rainfall is the same for both, stemflow is the cause for this striking difference in net precipitation and apparent interception. This confirmed season 2008 & 2009 findings (Chapter II; Bawain et al., submitted). We searched for a relation between net precipitation components and interception from rainfall and fog, time difference between to previous event, intensities of rain and fog, and stemflow-ratio. Rain and fog have a strong influence in precipitation budget, however, there is no clear relation between the stemflow-ratio and other parameters precipitation budget.

Next, the storage capacities were estimated according to the Leyton method. Theoretically stemflow and throughfall occur after water input events (rainfall or fog) with condition that canopy must be fully dry. However, this ideal condition is difficult to satisfy in cloud forest due to the presence of fog which although rainfall event stops the canopy may have a certain degree of wetness. For season 2010, throughfall express 71% of the rainfall for species A and 65% of rainfall for species B. This finding is consistent with the results of Matsubayash et al., 1994 in broad leaf and conifers. The percentages of throughfall from rainfall for both species are approximately equal. Many studies estimate the canopy storage (**Sc**) by plotting throughfall versus rainfall. The interception point on the throughfall axis is then assumed to be the magnitude of $\mathbf{S_C}$ (Leyton et al., 1967; Gueva-Escobar et al., 2007; Xiao et al., 2000; Yusop et al., 2003). We plotted throughfall (and stemflow) and gross rainfall for events with a time difference to previous events greater than 8 hours for both species. By applying the Leyton method, the storage capacity for species A and species B were estimated (Figs. 4.9 & 4.10). For high rainfall events, canopy storage and stem storage for species A is greater than canopy storage and stem storage for species B. Although the results are interpretable, the Leyton storage capacity approach does not take fog into account and therefore misses an important component in the cloud forest water balance. Because fog wets the canopy and stem surface to a certain degree during the season. When rainfall or fog event occur the storages (canopy and stem) are not completely empty. They are even partially filled or full, which allows all water to flow down to the ground, under the assumption that during fog occurrences evaporation can be neglected. In fact, the temporal variation of stemflow and throughfall during event 21 to 24 august support the idea that there is no difference in the storage capacities for both species (figure 4.5 and 4.6), but rather a difference in the collection body size that response for species B collects more water than species A.

In addition, the instrument sensitivity is a critical issue in cloud forests. The instruments used in this study are tipping buckets and at low rain intensity, it takes quite long to trigger a rain tip. Especially at the beginning of the event this leads to late rainfall starts. Hence, rainfall actually starts after throughfall or stemflow, simply because the gauges are not sensitive enough. The reason for this is the type of rainfall and the fog. Rain comes down as drizzle and it has low intensity. For cloud forest research with such low intensity rainfall standard instruments are at their limits. It is difficult to determine the timing exactly due to the low intensity and the instruments resolution.

## 4.4 Conclusion

This research investigates lag time of throughfall and stemflow and storage capacity for two tree species in a semi arid cloud forest. Lag time, start and end of events were identified by rain occurrence, and next modified by fog, throughfall and stemflow. It shows that throughfall starts earlier than stemflow for each individual tree species. In other words, throughfall takes shorter time till it starts after rain/fog event for both species. While, stemflow takes a longer time to start after rain or fog input.

In comparison between the two species A and B, throughfall for species B starts and ends earlier than throughfall of species A. In contrast, stemflow for B starts and ends later stemflow of A. According to the Leyton method for canopy and trunk storage capacities shows that canopy storage for species A is higher than species B. Although the results are interpretable, the approach of estimating storage capacity does not take fog water in account, which is an important factor in cloud forest.

Whereas the Leyton method suggests different storage capacities results from the high resolution precipitation budget show that the storage capacities are very similar. Consequently, the difference in stemflow between the two species cannot be attributed to different storage capacities but to the fact that the two species collect different amounts of rain and fog water.

In a cloud forest more sensitive instruments are require to record the reaction of the parameters. The average difference between start of species A and species B for throughfall and stemflow is close. The time difference between the two trees species are very close to the interval measurement of instruments (15 minutes). This leads us to conclude that it is difficult to determine the timing exactly as of to the low intensity and the instrument resolution.

This research confirms results of the previous years (2008 and 2009) for the net precipitation components fraction (stemflow and throughfall to net precipitation) for two tree species and that *Leucaenia leucacephala* species captures more water than *Pithicellobium dulce* through stemflow, taking in account that throughfall for both tree species are approximately equivalent.

By utilizing high resolution data for within-event stemflow variability it could be shown that the difference in stemflow between species A and B cannot stem from differences in storage capacity. It is rather the different amounts of water captured by the two species, so to say the efficiency with which the species capture both fog and rain water. Thereby, bark type and branches angle most probably plays a role in the amount of stemflow collection.

**Table 4.6.** Symbols used in chapter IV

| Symbol | Description | | Value/Units | Equation |
|---|---|---|---|---|
| $l_{corrected}$ | Pipe length | L | m | 1,2 |
| $a$ | Actual pipe length | L | m | 1 |
| c | Height of pipe end from ground to tree branch | L | m | 1 |
| $h$ | Height of the lowest pipe end from ground to funnel edge | L | m | 1 |
| $A_{Pipe}$ | Pipe area | $L^2$ | $m^2$ | 2 |
| $D_{Pipe}$ | Pipe diameter | L | m | 2,3 |
| $A_{Total}$ | Surface collecting area | $L^2$ | $m^2$ | 3 |
| $A_{Funnel}$ | Funnel area | $L^2$ | $m^2$ | 3 |
| $P_{SF}$ | Stemflow of the plot | $LT^{-1}$ | mm $d^{-1}$ | 4,5 |
| $V_{SF}$ | total stemflow volume | $L^3$ | liter | 4 |
| $n_{obSt}$ | Number of measured stems | - | - | 4 |
| $n_{totalSt}$ | Total stems number within a plot | - | - | 4 |
| $A_P$ | The plot area | $L^2$ | $m^2$ | 4 |
| $t$ | The Time between two consecutive measurements | T | d | 4 |
| $P_{TF}$ | Throughfall of the plot | $LT^{-1}$ | mm $d^{-1}$ | 5 |
| $P_{Net}$ | Net Precipitation | $LT^{-1}$ | mm $d^{-1}$ | 5,6 |
| $P_{Rain}$ | Gross Rainfall | $LT^{-1}$ | mm $d^{-1}$ | 6 |
| $I_a$ | Apparent interception | $LT^{-1}$ | mm $d^{-1}$ | 6 |
| $S_{En}$ | Event start | T | hour | 7 |
| $S_{Rn}$ | Rain event | T | hour | 7 |
| $1h$ | One hour | T | hour | 7 |
| $Lag\_S_{T_{TH}}$ | Lag start time of throughfall | T | hour | 8 |
| $S_{T_{R\|\|F}}$ | Start time of rain or fog which start first | T | hour | 8,9 |
| $S_{T_{TH}}$ | Start time of throughfall event | T | hour | 8 |
| $Lag\_S_{T_{ST}}$ | lag start time of stemflow | T | hour | 9 |
| $S_{T_{ST}}$ | Start time of stemflow | T | hour | 9 |
| $Lag\_E_{T_{TH}}$ | Lag end time of throughfall | T | hour | 10 |
| $E_{T_{R\|\|F}}$ | End time of rain or fog which ends later | T | hour | 10,11 |

**Table 4.6.** Symbols used in chapter IV (continue..)

| Symbol | Description | Value/Units | | Equation |
|---|---|---|---|---|
| $E_{T_{TH}}$ | End time of throughfall event | T | hour | 10 |
| $Lag\_E_{T_{ST}}$ | Lag end time of stemflow | T | hour | 11 |
| $E_{T_{ST}}$ | End time of stemflow | T | hour | 11 |
| $D_{T_{TH}}$ | Duration of throughfall | T | hour | 12 |
| $E_{T_{TH}}$ | End time of throughfall | T | hour | 12 |
| $S_{T_{TH}}$ | Start time of throughfall | T | hour | 12 |
| $D_{T_{ST}}$ | Duration of stemflow | T | hour | 13 |
| $E_{T_{ST}}$ | End time of stemflow | T | hour | 13 |
| $S_{T_{ST}}$ | Start time of stemflow | T | hour | 13 |

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# Chapter V

## Synthesis

Vegetation cover in the Dhofar mountains, Oman is shrinking due to over grazing and scarcity of rainfall. In addition, human activities associated with rapid development in all sectors further diminish the vegetation cover. To limit such problems many enclosures were created and distributed over the mountains which are affected by the monsoon season (locally called Khareef). Enclosures are protected areas used for plant and protect trees from grazing and human activities launched in 1992. There are 27 enclosures with 120 hectares in total area containing a total of 93344 trees of. Moreover, there are seven enclosures of total area of 27 hectare used for seed production.

The field study was conducted in the coastal mountain range (Jabal Al-Qara) in the Governorate of Dhofar, Oman. Measurements were conducted at the Tawi Attair forest enclosure ($17^o$ 6' 42"N, $54^o$ 31' 27"E, 650 m amsl), a fenced site of about 48576 $m^2$ (184mX264m), located on a plateau. The vegetation outside the enclosure is dominated by grass vegetation. Data for this study were collected within an experiment site at the southeast corner of the enclosure. The experiment site occupies a total area of 7 000 $m^2$.

Within the experiment site, six plots were delineated around tree clusters of the same species and at different positioning towards the windward edge. Of the six plots, four consist of *Pithicellobium dulce* trees and two of *Leucaenia leucacephala* trees.
Considering the size of the experimental site, climatic conditions can be assumed equal. Soil texture throughout the experimental site is characterized as clayey with a homogenous distribution.

The objective of this research was to measure net precipitation (stemflow and throughfall) at small-scale in a semi arid cloud forest and to have an improved understanding how net precipitation is effected by location or alternatively by tree species. Moreover the identification of large infiltration fluxes from stemflow (sources point) and throughfall (dripping point) under canopy was done. The time stability of those fluxes patterns and the role of outliers and their return probability was investigated. In addition, the lag time between water input to the system (rainfall and fog events) and net precipitation components (throughfall and stemflow) for two trees species (*Pithicellobium dulce* and *Leucaenia leucacephala*) were measured to estimate the storage capacities for stemflow and throughfall for both species.

Tree species plays a larger role than tree position for net precipitation heterogeneity in this cloud forest environment, in particular through stemflow differences. *Leucaenia leucacephala* species gains more rainfall and fog droplets than *Pithicellobium dulce* trees. This additive source might either stem from wind driven rain or horizontal precipitation. In either case, it enhances heterogeneity of water influx to the soil and creates points of extremely enhanced fluxes. Additional, horizontal precipitation increases the total amount of water available. Both, the increased heterogeneity as well as the horizontal precipitation have a potential to enhance the water movement through forest soil toward the aquifers.

## 5.1 Summary

This research is divided into five chapters. The first chapter introduces general information about the study location and the region features. It also, gives important details about the experiment, the general objective of the whole research and overview of chapters.

Chapter II deals with heterogeneity of net precipitation in a semi arid cloud forest on the Arabian Peninsula (Dhofar, Oman). As an example, an enclosure in an isolated area is used to study the influence of tree species and edge effect on the stemflow and throughfall for two tree species *Leucaenia leucacephala* and *Pithicellobium dulce*. Cloud capture by vegetation is a significant proportion of the water received at the ground (up to 37 % in addition to rain). Cloud capture partly compensated for interception loss, and in *Leucaenia* led to a net gain of water on the seasonal scale. Differences in net precipitation were mostly due to vegetation types than to location (distance to the edge). Significant differences in net precipitation were frequently (50% of the sampling periods) observed between plots of different species, with one species (*Leucaenia*) always achieving higher yields, independent of location. At the same time net precipitation was less frequently (25% of the sampling periods) elevated at the edge, compared to the interior. Differences in net precipitation between species were almost entirely due to differences in stemflow. While absolute values of throughfall did not differ much between species, absolute values of stemflow were double for *Leucaenia* compared to *Pithicellobium.* Results propose that species identity governs the efficiency of cloud capture and by doing so it enhances the spatial heterogeneity of infiltration possibly with implications for ground water recharge.

Chapter III investigates the heterogeneity of below canopy fluxes and particularly the sources of enhanced canopy drainage fluxes (stemflow versus throughfall dripping points), measurements of stemflow from two wet seasons and small-scale measurements of throughfall (square of 7 m x 11 m with 0.5 m grid spacing) over 21 individual days were used. We investigated, which of these sources creates more likely points of high infiltration rates, how stable this pattern is in time and what is the return probability of outliers of stemflow and throughfall. Generally, throughfall contributes more to overall water arriving below the canopy. The overall time stability is comparable, and also outliers had a tendency to re-occur at the same spot for both stemflow and throughfall ($P_{TF}$=0.41, $P_{SF}$>0.15). Thus, the same place would repeatedly receive extremely enhanced fluxes. However, outliers in stemflow contributed more for total received flow, than outliers in throughfall, indicating that certain individuals had properties specifically conducive for producing stemflow. In this cloud-influenced environment, throughfall was enhanced under denser canopy, probably due to enhanced cloud capture. The most intensive below canopy fluxes are to be expected from specific tree individuals.

Chapter IV investigates the difference in time between input water events to the system (rainfall and fog) and net precipitation components (stemflow and throughfall) for the 2010 season. Automatic loggers for all measurements parameters are used. Data was collected on 15 minutes increments, different relations between parameters were created to estimate lag time and storage capacity of two tree species. It is logical that throughfall and stemflow take place after rainfall or fog events with a condition that the canopy storage capacity and stem storage capacity are fully saturated. Throughfall was found to start earlier than stemflow for both tree species. The study shows that throughfall in all seasons for trees species is approximately equal while the stemflow for *Leucaenia* is twice than stemflow for *Pithicellobium*. Furthermore, the storage capacity for *Pithicellobium* is greater than *Leucaenia* and stem capacity for *Leucaenia* is greater than *Pithicellobium* this due to the size, bark smoothness and duration.

## 5.2 Conclusions

Heterogeneity of net precipitation (precipitation below canopy) in semiarid region cloud forest was studied for two tree species *Leucaenia* and *Pithicellobium*. The research proves that tree species plays an essential role in effecting the heterogeneity net precipitation, which is more important than the edge effect at the Tawi Attair enclosure. Moreover, stemflow in this environment is found to be an important pathway for channeling water to the ground and modifying available water in the plots of different species. Therefore, stemflow could play an important role as a point source for groundwater recharge. In addition, the fractional of throughfall and stemflow is constant at the edge and at the interior of the forest for both species (*Pithicellobium* and *Leucaenia*). This proves the importance of tree species than the location on the heterogeneity of net precipitation. *Leucaenia* tree species is found to capture more horizontal precipitation than *Pithicellobium*. Our study emphasizes that tree species effects can play a role comparable or even more important than the more often cited edge effect for shaping net precipitation in cloud forests.

Stemflow contributes much larger on water availability at the soil surface beneath canopy than throughfall. The net precipitation components show spatial stability. However, stemflow contributes a larger fraction of water to the total and occur more persistently at the same spot. Looking to the effects of individual stemflow, stemflow contribute mostly to creating hotspots of infiltration in this environment. This phenomenon is clear around stems with a larger yield.

Lag time of throughfall and stemflow in a semi arid cloud forest for different tree species differs. The average time gap between input events (rainfall or fog) and stemflow and throughfall differs, between species, however, the differences are small. Overall, throughfall reacts faster to the input than stemflow. In other words, throughfall takes a shorter time till it starts after rain/fog event for both species while, stemflow takes longer time to start after the events occur. The bark type, branches angle and the height of trees play a role in the mount of stemflow volume collection and the duration for water to reach the ground below canopy.

## 5.3 Future work

This research studied net precipitation heterogeneity under two trees species in a semi arid zone. It is able to prove that the trees species strongly effluence the net precipitation more than edge effect, which believes the case in widely studied over the world. Moreover, stemflow contributes a larger fraction of water to the total.

In a small scale, the flux of stemflow and throughfall show spatial patterns indicating stability over the time for both. However, throughfall fluxes per plot are generally larger than stemflow. Besides, stemflow fluxes create hotspots at the soil surface. Although outliers occur frequently for net precipitation components (stemflow and throughfall), stemflow outliers contribute more to the total water received than throughfall outliers.

Studying more sites within the region for different trees species and comparing the results would help to create concrete knowledge about the cloud forest in Dhofar. Moreover, those studies will give a good management for existing enclosures and guide authorities in the establishment of new enclosures professionally. In sequence, there is an essential requirement for developing conceptual models to study the ground water recharge beneath those trees; especially since there is adequate input data (hydrological and climatologically). The model will present a clearer picture about ground water recharge from the cloud forest toward the coastal aquifers. The aquifers are the main water supply source for different water usages in this region.

## Danksagung/ Acknowledgements

I would like to express my thanks to my supervisors Jun.-Prof. Dr. Anke Hildebrandt, Dr. Jan Friesen and Prof. Dr. Sabine Attinger for their continuous encouragement, support, help and constructive comments and discussions.

I am grateful for ministries of regional municipalities and water resources and ministry of environment and climate affairs for funding this study. Also, I thank staff of both ministries for their help in field work.

Special thanks go to the staff of Oman embassy in Berlin for their care and follow-up during the period of study and to Omanis students in Germany without exception.

Last but not least, thanks to my family for their patience and understanding over years of this study.

I would like to express my thanks to the following people:

Gassan Al Tameami, director of the human resources development, Dr. Abdul-Aziz Al Mushaiki, assistant of the DG, Eng. Hammed Al Hatmi the DG of water resources, Eng.Salim Alesh Salalah water resources director, Salim Farj Abdoon Al Huzali, the DG of environment and climate affairs Dhofar and staff of monitoring and studies section at Salalah office.

# Selbstständigkeitserklärung

Ich erkläre, dass ich die vorliegende Arbeit selbstständig und unter Verwendung der angegebenen Hilfsmittel, persönlichen Mitteilungen und Quellen angefertigt habe.

Jena, 12.Mai 2012

Unterschrift des Verfassers (Abdullah Mohammed Ali Bawain)